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REVIEW

A review of the current status of *Kappaphycus alvarezii*-based biostimulants in sustainable agriculture

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Abstract

The indiscriminate or non-strategic use of chemical fertilizers in agriculture can potentially have adverse effects on natural ecosystems due to their harmful impacts. As a cleaner, more sustainable supplementary treatment to minimize the need for synthetic nutrient inputs, seaweed-based biostimulants (phyco[bio]stimulants) are being widely studied to increase agricultural productivity for the burgeoning global population. *Kappaphycus alvarezii*, a fast-growing, tropical red alga widely cultivated for its hydrocolloid content, is a promising source of bioactive compounds that improve plant growth, including imparted tolerance to some levels of abiotic and biotic stressors in harsh environmental conditions. The alga also contains protein, carbohydrates, fatty acids, fibres, algal hormones, polyphenols, and various macro- and microelements. The polysaccharide κ-carrageenan, a major constituent of this particular seaweed, also has known plant growth-stimulating effects. Thus, various *K. alvarezii*-based biostimulants are used in agriculture, including liquid extracts and solid formulations which are applied as: drenches, foliarly and seed coatings, or seed soaking. These groups of biostimulants are reported to increase growth, yield, nutrient uptake, and biotic and abiotic resilience, depending on the type of extraction method, concentration of the applied extract, and also timing of the application within the treated plant's growth cycle. This review summarizes various *K. alvarezii*-based products used in agriculture for plant biostimulation, their extraction procedures, application modes, and proposed mechanisms of action. We reviewed the scientific data supporting the use of *Kappaphycus* extracts as biostimulants to enhance crop productivity and quality. Additionally, the beneficial impacts of using *Kappaphycus* extracts on soil health and their potential as a sustainable, adaptive strategy for addressing climate variability is discussed. Several research gaps have been identified to understand the current limitations of the existing knowledge base, and a way forward has been presented to prioritize areas for further investigation.

Keywords Seaweed sap/extract · Biostimulant · *Kappaphycus alvarezii* · Red alga · Climate change · Sustainable · Resilient agriculture · Rhodophyta

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Introduction

The 2030 Agenda for Sustainable Development adopted by United Nations, identified 17 goals aimed at maintaining peace and prosperity for humanity. Key amongst these goals: "responsible consumption and production," "zero hunger," and "climate action" need to be achieved while ensuring food security for the growing population. To meet this challenge, it is essential to increase agricultural production while minimizing environmental impacts. Sustainable production techniques such as conservation agriculture, to increase resilience, integrated plant nutrient management, natural resource management, and the use of agricultural inputs with low carbon footprints, have been suggested as requirements to responsibly increase crop productivity.

Biostimulants are gaining prominence globally as one method to meet these challenges. The US 2018 Farm Bill defined biostimulants (Sible et al. 2021), while the EU included them as a distinct category under the regulation of fertilizer products (Ricci et al. 2019). India's Gazette publication in Feb. 2021 spelled out categories, including seaweed extracts. Such regulatory frameworks encourage biostimulant use in agriculture and boost their need for manufacture. Seaweed-based biostimulants (phyco[bio] stimulants) are the most researched members of the biostimulant category and improve plant growth, defense, and nutrient-use-efficiency (Shukla et al. 2019, 2022). Various seaweeds have long been used as an amendment for soil (Buschmann et al. 2017). The red, tropical seaweed, *Kappaphycus alvarezii* has gained increasing importance in recent years as a source of various types of biostimulant extracts (da Costa et al. 2017; Begum et al. 2018; Carillo et al. 2020; Del Buono 2020; El Boukhari et al. 2020; Wozniak et al. 2020).

Ghosh et al. (2015) and Singh et al. (2018) showed that *Kappaphycus*-based biostimulants can play a significant role in crop intensification with limited environmental trade-offs. Members of this seaweed genus have a high growth rate and can be relatively easily cultivated leading to their being responsible for significant carbon assimilation (Mantri et al. 2017b). Biostimulants made from biomass of this genus and in particular the species *K. alvarezii* have lower carbon and fresh water footprints than fertilizers (Singh et al. 2018) and are also reported to enhance crop yields (Pramanick et al. 2014a; Raverkar et al. 2016; Mantri et al. 2022). Their use ultimately reduces the units of carbon and water associated with each unit of food production, contributing to the reduction of greenhouse gas emissions to the atmosphere (Ghosh et al. 2015; Sharma et al. 2017; Singh et al. 2018). Climate change can exacerbate environmental stress, drastically diminishing crop productivity and adversely affecting rhizospheric soil microbes (Trivedi et al. 2022b). *Kappaphycus*-based biostimulants have been demonstrated to ameliorate soil moisture stress by modulating biochemical and microbiological parameters (Trivedi et al. 2022b). The implementation of biostimulants sourced from this economically important, cultivatable alga can yield positive socio-economic results throughout the entire value-chain, leading to the betterment of seaweed growers' livelihoods (i.e., the marine farmers) and the associated industry employees, as well as an increase in terrestrial farmers' income upon the application of these products to crops (Mantri et al. 2017b, 2022). As such, it is imperative to provide a thorough review of the diverse categories of available biostimulants derived from *K. alvarezii* and the advantages for crop quality and productivity that can be gained from their use. This review emphasizes essential research that has established the basis for comprehending the active components of this red seaweed and their functions in treated plants, such as their mechanisms of action, as well as the optimal application frequency and dosage for achieving the maximum benefits. Furthermore, this review aims to shed light on required areas for future research and development.

Kappaphycus alvarezii cultivation and biomass valorization for various applications, including biostimulants

Kappaphycus alvarezii (Doty) L.M. Liao, is a red alga also known by its commercial names of ‘cottonii' and ‘Elkhorn sea moss', that is widely cultivated in tropical waters since the early 1970s. It is especially cultivated in Asian countries such as Indonesia, the Philippines, Vietnam, Zanzibar and Malaysia. It is mainly cultivated for its cell wall polysaccharides i.e., predominantly κ-carrageenan (κ-Cg) (Hayashi and Reis 2012) for use in many applications such as highly processed food. Figure 1 shows the structure of κ-Cg along with ι- and λ- carrageenans. Other significant uses of cultivated *K. alvarezii* biomass are its commercial-scale application for non-rheological purposes, such as the production of reduced graphene oxide (Sharma et al. 2014), chemicals (i.e., potassium sulfate fertilizer and hydroxymethyl furfural), water purification (Mondal et al. 2013), bioethanol (Khambhaty et al. 2012; Meinita et al 2012), food supplements (Wanyonyi et al. 2017), animal feeds (Sharma and Datt 2020) and health supplements (Sharma et al. 2019), etc. (Fig. 2). However, since the development of an integrated carrageenan and plant biostimulant technology (Eswaran et al. 2005), the use of its raw material as a biomass for the industrial production of plant biostimulants has increased considerably (Hurtado et al. 2021). Dried cultivated *Kappaphycus*

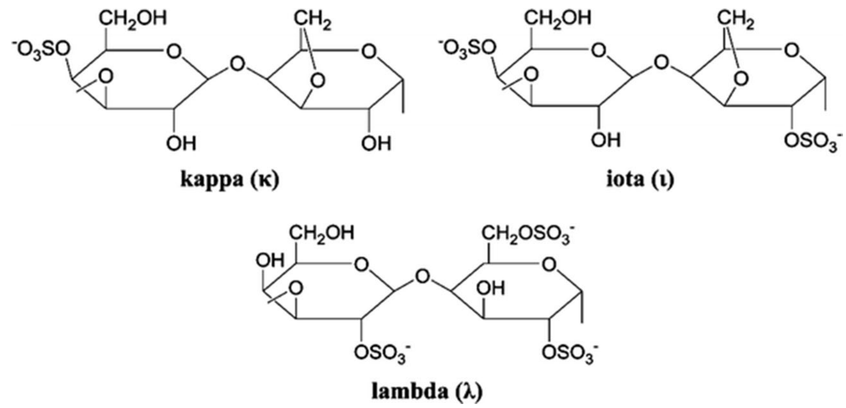

Fig. 1 Structures of three major types of carrageenan: kappa-, iota-, and lambda-. [Reproduced from Chauhan and Saxena 2016]

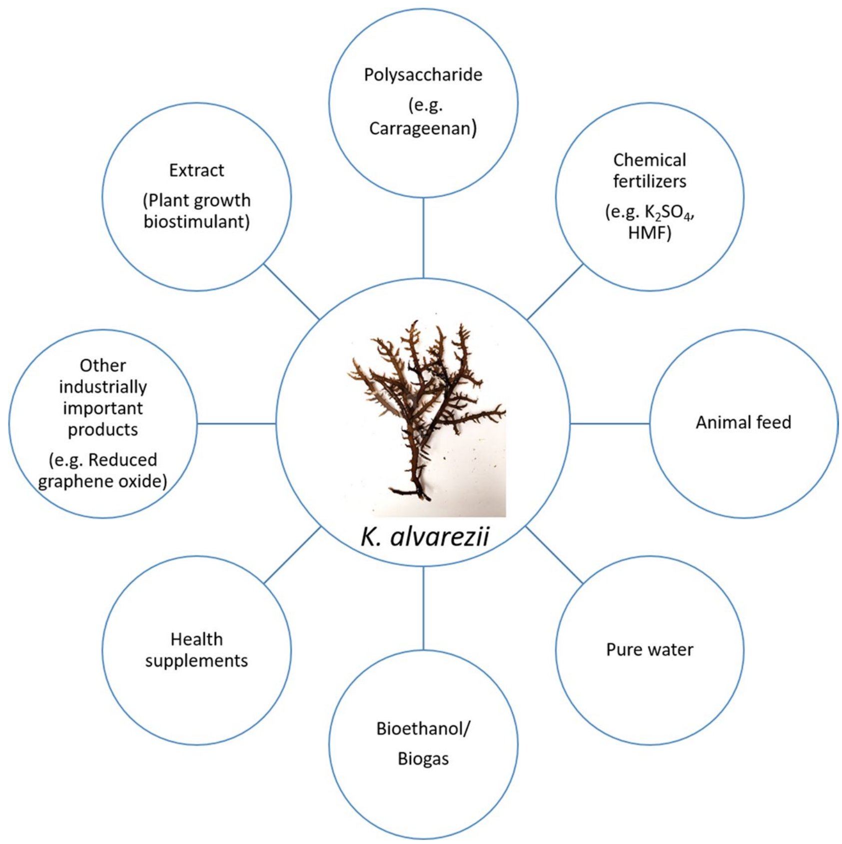

Fig. 2 Reported applications of *Kappaphycus alvarezii* seaweed. HMF: hydroxymethyl furfural; K_2SO_4: Potassium sulphate

biomass is known as RDS (i.e., Raw Dried Seaweed) and has a moisture content of around 35%.

The first successful cultivation of *K. alvarezii* was achieved in the Philippines in the 1970s (Mantri et al. 2017b). Since then, the global fresh weight production of *K. alvarezii* reached 1.6 million tonnes, valued at US$ 215 million in 2018 (FAO 2020). These values are provided here for comparative purposes only and recently the veracity of these values was questioned (See Steven Herman's http://www.phyconomy.net and Hatch Blue's http://www.seaweedinsights.com/. for evolving details; accessed July 2023). Southeast Asian countries have almost 60% of the world's cultivation sites (Hurtado et al. 2019). This is mainly because of the favourable geographical area for cultivation within ± 10° latitude (Hayashi et al. 2010). A series of videos on eucheumatoid seaweeds amongst which *K. alvarezii* is a member were made available by the Tropical Seaweed Coalition Development workshop which is maintained at www.phyconomy.org (accessed July 2023).

Kappaphycus alvarezii has a high average daily growth rate (DGR) of up to 10.7% when cultivated using the bamboo raft technique (Hayashi et al. 2010), yielding up to 150–200 kg fresh biomass, in a 45-day cycle, from a 3 × 3 m bamboo raft (Ghosh et al. 2015; Mantri et al. 2017b). Various cultivation methods have been used, including fixed off-bottom (for shallow areas), hanging long-line fixed and swing (for deeper areas), monoline, tube-net, multiple-raft long-line (such as bamboo raft, PVC pipe rafts) (Hayashi et al. 2010; Mantri et al. 2017a). The average DGR reported was 0.2–5.3% day^{-1} and 0.5–10.7% day^{-1} for fixed off-bottom and raft methods, respectively (Hayashi et al. 2010). Growth rates, biomass, yield, and carrageenan quality greatly depend on the water quality (Simatupang et al. 2021) variety/strain, cultivation technique, period of growth (i.e., 30, 45, and 60 days), and water depth (Hurtado et al. 2021).

In 1984, CSIR—Central Salt & Marine Chemicals Research Institute (CSMCRI) introduced a strain of *K. alvarezii* of Philippine origin into quarantine in Indian waters and employed floating bamboo rafts with nets laid out at the bottom to reduce losses due to grazing by herbivorous fish. Tube-net methods were also adopted in waters with a high current, allowing the thalli to grow in open water (Mantri et al. 2017b).

Globally, a number of commercial seaweed products derived from *K. alvarezii* biomass are used in agriculture (Table 1) and have a known significant impact on crops. Whilst the un-processed RDS biomass, when added to the soil, can act as a soil conditioner due to its water binding nature, its various liquid and κ-Cg extracts are effective as biostimulants and primers of plant biotic responses. In particular, κ-Cg and its oligo-saccharides are known to improve the growth of treated plants by modulating physiological and biochemical processes involved in stress tolerance and nutrient-use-efficiency (Shukla et al. 2016; Deolu-Ajayi et al. 2022).

Kappaphycus alvarezii biostimulants: Extraction methods and formulations

There are several methods available to extract *Kappaphycus* biomass, including simple liquefaction by crushing it while still wet, hydrolysing it with acid or alkali, or using hot and/or cold water-based extraction methods. These individual or combined extraction methods are utilized to produce different types of biostimulatory products.

Table 1 Commercial *Kappaphycus alvarezii*-based plant biostimulant products

Product name	Company	Claimed benefits
AquASap	AquAgri processing Pvt. Ltd., India	Improves plant growth and yield
AquAsap Powder	AquAgri processing Pvt. Ltd., India	Improves plant growth and yield
AquAsap Granules	AquAgri processing Pvt. Ltd., India	Improves plant growth and yield
Deep gel algae	Prasmo Agri, Kumbakonam, India	Maintains soil health, soil microbes and improves root growth and overall plant productivity
Superblooming Agent – Phoolan	Pindfresh, India	Improves fruit quality, provides better economical benefits, helps in maintaining soil health, improves plant's stress tolerance capacity
Sagarika concentrated liquid	IFFCO, India	Improves plant growth and yield
Sagarika granules	IFFCO, India	Improves plant growth and yield
Kappaphycus Liquid Red Algae Extract	Agrocare, India	Improves plant growth and yield
First Class Dried Seaweed *Kappaphycus alvarezii*	Lakshmi Enterprises, India	To extract carrageenan for subsequent industrial applications
Brown Red Green *Kappaphycus* Seaweed	PSSGT Nextgen Export, India	Uses for carrageenan extraction for its further industrial applications
Agricota	Orgkapp, Ecuador	Helps to regulate physiology of the plant and improves its metabolic balance
Tarma	Sea6Energy, India	Having bioavailable potash for easy absorption of nutrients by plants
Agrogain®	Sea6Energy, India	Increases photosynthetic activity, nutrient uptake and metabolism of the plants
Tomatough®	Sea6Energy, India	Enhances anti-bacterial response
AgFort®	Sea6Energy, India	Provides disease resistance to plants by activating its immune pathways
Magic vita – P	HVG Industries, Chennai, India	Increases withanolides production in in-vitro shoot cultures of *Withania somnifera*

® denotes registered trademark

Strained Seaweed Extract (SSE)

A process for the production of κ-Cg (a hydrocolloid) along with liquid biostimulant from fresh *K. alvarezii* biomass was described by Eswaran et al. (2005), henceforth referred to as SSE. The process requires homogenization of fresh thalli and filtering them through a muslin cloth. The liquid has been beneficially applied at various dilutions to different crops the remnant fibrous material is dried and used for carrageenan extraction.

Boiled Seaweed Extract (BSE)

BSE of *K. alvarezii* was produced by boiling fresh seaweed in water (1:100 w/v) for 15 min at 100 °C, filtering, and cooling the resulting filtrate at room temperature (Banu et al. 2020).

Lyophilized Seaweed Extract (LSE)

Fresh seaweed was lyophilized, powdered, and mixed in deionized water at a ratio of 1 g per 10 mL. The resulting suspension was centrifuged, and the supernatant was lyophilized and powdered again (de Araújo Amatuzzi et al. 2020). The resulting extract is referred to as LSE in this article and has been used at various dilution levels.

Strained Seaweed Extract Acid Hydrolysate (SSEAH)

In a patent (Nori et al. 2019), the SSE obtained as described previously was mixed with concentrated acid hydrolysate of the pulp, which contained soluble oligo-sulfated galactans, resulting in a mixed extract known as strained seaweed extract acid hydrolysate (SSEAH). AgroGain® is a formulation made using SSEAH, along with suitable carriers, diluents, and excipients that improve plant growth and stress tolerance (Nori et al. 2019; Sahana et al. 2022).

Girish et al. (2020) reported a method to prepare a *Kappaphycus*-based biostimulant rich in sulfated galactose and de-polymerized polysaccharides using acid hydrolysis. The low molecular weight fractions from SSEAH has been reported to induce natural immunity against different pathogens in plants (Banakar et al. 2022; Roy et al. 2022). Different biostimulant formulations (i.e., LBD1, LBD3, and LBD12) have been prepared using SSEAH. The products LBD3 (Tomatough®) and LBD12 (AgFort®) contain molecular weight fractions of sulfated galacto-oligosaccharides that are less than 5 kDa and less than 1 kDa, respectively (Roy et al. 2022). SSEAH-based formulations have been commercialized by Sea6 Energy Private Limited (Bangalore, India).

Minimally Processed Homogenate (MPH)

An extract of dry *K. alvarezii* (RDS) was prepared by homogenizing it with water in a ratio of 1:6 (w/v) for 30 min. The resulting slurry was filtered through a 200 mesh sieve and the filtrate was dried to a water-soluble powder using a triple-effect evaporator, yielding the extract in powdered form and henceforth called MPH (Vaghela et al. 2023).

Composite Seaweed Extract (CSE)

Shinde and Madathil (2018) from Heliae Development LLC (Arizona, USA) reported the production of bioactive formulations by lysing seaweed thalli. They subjected the harvested *Kappaphycus* thalli to a solvent-based extraction process (utilizing alkali such as NaOH or KOH, acid, and ethanol) at an elevated temperature (i.e., 90–95 °C). The extracts obtained were combined and concentrated and henceforth reported as CSE and formulated as a biostimulant.

Kappaphycus alvarezii SSE has been widely studied and reported. It is utilized in a commercial formulation, as a blend of red seaweed *K. alvarezii* and brown seaweed, by M/s AquAgri Processing Private Limited (Manamadurai, India) and marketed under the brand name "Sagarika" in high volumes by the Indian Farmers Fertilizer Cooperative Limited (IFFCO), New Delhi, India (Annual report 2021). *Kappaphycus alvarezii* is a rich source of κ-Cg, which is also a biostimulant. It can be extracted through a hot alkali extraction method (Eswaran et al. 2005).

Components of *Kappaphycus alvarezii* and their activities

Until approximately 15 years ago (i.e., 2005), there was only one need for estimating the chemical composition of *K. alvarezii*, which was its primary use as a source of κ-Cg (Reddy et al. 2003). However, applications of the cultivated biomass emerged for the purpose of manufacturing various types of biostimulatory extracts for agriculture. Even though *K. alvarezii* is a tropical seaweed, the chemical composition of the biomass is known to vary widely based on the geographic location of the cultivation sites and even seasonally, at the same site of cultivation (Kumar et al. 2015; Araújo et al 2022) (Table 2). Seawater temperature, salinity and nitrate concentration are some of the major environmental and physical factors that significantly influence the chemical composition of this type of seaweed (Kumar et al. 2015).

The macro- micronutrients and proximate composition of whole, dried *K. alvarezii* cultivated at selected Indian and Malaysian sites (Table 2) varied by 9.8–19.3% between the study sites. Similarly, the lipid and ash contents varied between

Table 2 Reported chemical compositions of whole *Kappaphycus alvarezii* (red seaweed) and its extracts

Parameter	Content of dry *K. alvarezii* (Kumar et al. 2015)	Content of dry *K. alvarezii* (Yong et al. 2015)	Content of liquid extract/sap of *K. alvarezii* (Rathore et al. 2009)	Content of lyophilized powder of *K. alvarezii* liquid extract/sap (Vaghela et al. 2022)	Content of liquid extract/sap of *K. alvarezii* (Mondal et al. 2015)	Content of liquid extract/sap of *K. alvarezii* (Shanmugam and Seth 2018)*	Content of concentrated liquid extract/sap of *K. alvarezii* (Karthikeyan and Shanmugam 2017)#
Physical properties							
pH	-	-	-	-	-	6.5–7.2	8.5 (1% solution)
Total organic matter	-	-	-	-	-	0.65–0.81%	5.08%
Total soluble solid	-	-	-	-	-	3.52–4.47%	17.45%
Specific gravity	-	-	-	-	-	1.00–1.03 g cm^{-3}	1.05 g cm^{-3}
Electrical conductivity	-	-	-	-	-	-	59.1 dS m^{-1}
Moisture Content	-	-	-	-	-	-	82.55%
Proximate composition							
Protein	19.25%	9.81%	-	3.4 ± 0.94 %	-	-	-
Carbohydrates	25.87%	-	-	5.7 ± 0.13 %	-	-	-
Fiber	14.52%	-	-	-	-	-	-
Lipid	0.64%	2.06%	-	2.13 ± 0.06 %	-	-	-
Ash	27.00%	38.86%	-	-	-	2.72–3.70%	12.37%
Macro elements							
Sodium	2.23%	Saturated	0.51%	1.67 ± 0.18%	1.3 g L^{-1}	-	1.34%
Potassium	4.10%	Saturated	1.97%	22.43 ± 1.8%	21 g L^{-1}	1.46–1.70%	11.28%
Phosphorus	0.12%	-	33.99 ppm	0.34 ± 0.05%	29 ppm	14–38 ppm	0.02%
Calcium	0.84%	0.076%	460.11 ppm	0.43 ± 0.0%	1.7 g L^{-1}	157–412 ppm	0.33%
Magnesium	0.74%	0.27%	581.20 ppm	0.27 ± 0.002%	2.1 g L^{-1}	152–370 ppm	0.32%
Sulphur	11.24%	-	0.06%	-	-	95–330 ppm	0.20%
Nitrogen	-	-	0.03%	1.98 ± 0.34%	85 ppm	180–265 ppm	0.15%
Micro elements							
Iron	659.4 ppm	ND	10.59 ppm	37.33 ± 4.7 ppm	10 ppm	-	0.03%
Copper	7.6 ppm	0.98 ppm	0.30 ppm	10.62 ± 3.65 ppm	300 ppb	-	200.7 ppm
Zinc	18.5 ppm	5.20 ppm	0.62 ppm	12.4 ± 2.4 ppm	7.7 ppm	-	3.13 ppm
Manganese	11.0 ppm	1.05 ppm	2.50 ppm	3.92 ± 0.5 ppm	2.8 ppm	-	5.93 ppm
Boron	28.1 ppm	-	-	-	2.8 ppm	-	7680 ppm
Bromine	-	-	-	-	41 ppm	-	-
Iodide	-	-	-	-	1.54 ppm	-	-
Iodate	-	-	-	-	0.44 ppm	-	-
Molybdenum	0.4 ppm	-	-	2.1 ± 0.7 ppm	-	-	-
Cobalt	5.6 ppm	0.44 ppm	-	-	-	-	1.18 ppm

Table 2 (continued)

Parameter	Content of dry *K. alvarezii* (Kumar et al. 2015)	Content of dry *K. alvarezii* (Yong et al. 2015)	Content of liquid extract/sap of *K. alvarezii* (Rathore et al. 2009)	Content of lyophilized powder of *K. alvarezii* liquid extract/sap (Vaghela et al. 2022)	Content of liquid extract/sap of *K. alvarezii* (Mondal et al. 2015)	Content of liquid extract/sap of *K. alvarezii* (Shanmugam and Seth 2018)*	Content of concentrated liquid extract/sap of *K. alvarezii* (Karthikeyan and Shanmugam 2017)#
Chloride	-	-	-	-	-	-	4.27%
Silica	-	-	-	-	-	-	0.88%
Chomium	38.8 ppm	ND	-	-	-	-	-
Cadmium	10.0 ppm	0.48 ppm	-	-	-	-	-
Mercury	0.5 ppm	-	-	-	-	-	-
Beryllium	-	ND	-	-	-	-	-
Lithium	-	0.82 ppm	-	-	-	-	-
Vanadium	2.1 ppm	0.64 ppm	-	-	-	-	-
Nickel	-	-	-	-	-	-	-
Aluminum	-	-	-	24.5 ± 2.3 ppm	-	-	-
Phytohormones							
Indole 3-acetic acid (IAA)	-	-	-	-	21.11 ppm	25.25–70.20 ppm	330 ppm
Kinetin	-	-	-	-	9.21 ppm	-	-
Zeatin	-	-	-	-	18.62 ppm	14.34–55.50 ppm	180 ppm
Gibberellin (GA_3)	-	-	-	-	25.72 ppm	52.44–140.70 ppm	550 ppm
Quaternary ammonium compounds							
Choline	-	-	-	-	60.71 ppm	-	-
Glycine betaine	-	-	-	-	78.47 ppm	-	-
Fatty acid composition							
Saturated fatty acids	-	59.32%	-	-	-	-	-
Monounsaturated fatty acids (MUFA)	-	13.80%	-	-	-	-	-
Polyunsaturated fatty acids (PUFA)	-	17.55%	-	-	-	-	-
Amino acid composition							
Alanine	-	-	-	-	-	-	0.022%
Arginine	-	-	-	-	-	-	0.034%
Aspartic acid	-	-	-	-	-	-	0.115%
Cysteine	-	-	-	-	-	-	0.019%
Glycine	-	-	-	-	-	-	0.028%

Table 2 (continued)

Parameter	Content of dry *K. alvarezii* (Kumar et al. 2015)	Content of dry *K. alvarezii* (Yong et al. 2015)	Content of liquid extract/sap of *K. alvarezii* (Rathore et al. 2009)	Content of lyophilized powder of *K. alvarezii* liquid extract/sap (Vaghela et al. 2022)	Content of liquid extract/sap of *K. alvarezii* (Mondal et al. 2015)	Content of liquid extract/sap of *K. alvarezii* (Shanmugam and Seth 2018)*	Content of concentrated liquid extract/sap of *K. alvarezii* (Karthikeyan and Shanmugam 2017)#
Histidine	-	-	-	-	-	-	0.04%
Isoleucine	-	-	-	-	-	-	0.12%
Leucine	-	-	-	-	-	-	0.12%
Lysine	-	-	-	-	-	-	0.08%
Tryptophan	-	-	-	-	-	-	0.023%
Methionine	-	-	-	-	-	-	0.070%
Phenylalanine	-	-	-	-	-	-	0.031%
Proline	-	-	-	-	-	-	0.010%
Serine	-	-	-	-	-	-	0.145%
Threonine	-	-	-	-	-	-	0.031%
Tyrosine	-	-	-	-	-	-	0.065%
Valine	-	-	-	-	-	-	0.035%
Glutamic acid	-	-	-	-	-	-	0.059%
Asparagine	-	-	-	-	-	-	-
Vitamins							
Vitamin C	-	-	-	2.09 ± 0.3 mg g^{-1}	-	-	26.419 ppm
Vitamin D	-	-	-	-	-	-	0.081 IU $(100\ g)^{-1}$
Vitamin B_2	-	-	-	-	-	-	0.006 ppm
Vitamin B_3	-	-	-	-	-	-	0.004 ppm
Vitamin B_5	-	-	-	-	-	-	0.026 ppm
Vitamin B_6	-	-	-	-	-	-	0.034 ppm
Carotenoids	-	-	-	0.64 ± 0.05 mg g^{-1}	-	-	-
Antioxidants composition							
Total phenolic	-	-	-	1108.67 ± 98.51 mg GA $(100\ g)^{-1}$	-	-	-
Total Flavonoids	-	-	-	15.26 ± 0.95 mg QE $(100\ g)^{-1}$	-	-	-

*values are of different seasons of the year, hence given in a range

#values are of five times concentrated (AquAsap-5X) liquid extract

0.6–2.1 and 27–38.9%, respectively. Carbohydrate and fibre contents were reported at approximately 25.9 and 14.5% (Kumar et al. 2015; Yong et al. 2015). A high ash content indicated the efficiency of *K. alvarezii* in absorbing various elements from surrounding seawater, e.g., potassium (Yong et al. 2015). *Kappaphycus alvarezii* is rich in macroelements, having high sulfur (11.24%), sodium (2.23%) and potassium (4.10%). Among microelements, iron was reported to have a maximum level of up to 659 ppm (Kumar et al. 2015).

Kappaphycus alvarezii has also been found to be rich in fatty acids. The powder of whole, dried *K. alvarezii* was reported to have a 2.1% lipid content, of which 59.3% was saturated, 13.8% was monounsaturated and 17.6% was polyunsaturated fatty acids (Yong et al. 2015). Palmitic acid (36.4%), palmitelaidic acid (8.6%), and eicosapentaenoic acid (10.3%) are the major fatty acids reported among saturated, monounsaturated and polyunsaturated fatty acids (Yong et al. 2015).

Other constituents, such as glycine betaine and choline chloride, have been reported in the SSE of *K. alvarezii* at 78.5 and 60.7 ppm, respectively, and have been shown to have beneficial roles in crop production (Mondal et al. 2015). Rathore et al. (2009) also reported the chemical composition of *K. alvarezii* SSE (Table 2). The alga was reported to possess a higher affinity for potassium over sodium absorption (Mondal et al. 2013), which explains the relatively high levels of potassium in virtually all of its extracts. Additionally, high-performance liquid chromatography (HPLC) and tandem mass spectrometry (MS–MS) revealed the presence of algal phytohormones such as indole-3-acetic acid (IAA), gibberellic acid 3 (GA_3), and zeatin in the SSE, with concentrations of 21.1, 25.7, and 18.6 ppm, respectively (Mondal et al. 2015).

Vaghela et al. (2022) found that the lyophilized SSE of *K. alvarezii* contained 0.4% calcium and 0.2% magnesium, as well as significant amounts of Fe, Cu, Mn, Mo, and Zn (i.e., 37.4, 10.6, 3.9, 2.1, and 12.4 mg kg^{-1}, respectively). On a dry weight basis, the lyophilized powder of SSE was reported to have 22.4% and 1.7% potassium and sodium, respectively (Vaghela et al. 2022). Recently, several bioactive compounds were identified in the lyophilized SSE of *K. alvarezii* that have significant, positive impacts on plants (Vaghela et al. 2022). These compounds include sulfabenzamide, kinetin, 1-phosphatidyl-1D-myo-inositol, C-16 sphinganine, and dodecanamide. More recently, several biologically active compounds, such as catechin hydrate, naringenin, cinnamic acid, cysteine, proline, methionine, phenylalanine, lysine, glutamic acid, glycine, leucine, putrescine and IAA, were identified in the MPH of *K. alvarezii* (Vaghela et al. 2023). Table 3 summarizes the specific beneficial bioactivities of these compounds when individually applied exogenously. Additionally, κ-Cg of *K. alvarezii* stands out as a particularly noteworthy ingredient that has been extensively studied, and its bioactive properties are well-documented (Shukla et al. 2016). A positive response of maize was found by application of kappa-oligocarrageenan with molecular weights of 42, 17 and 4 kDa that were derived from *K. alvarezii* (San et al. 2020).

Beneficial effects of *Kappaphycus alvarezii* extracts/formulations on plants and soil

Effects on seed germination and vigour

Babu and Rengasamy (2012) studied the effects of SSE on seed germination potential. Chilli, rice, and peanut seeds in a 1–2% extract, for 6 or 24 h, resulted in significantly higher radicle and plumule lengths and increased fresh weight of the treated seedlings. Similarly, the highest germination percentage of chilli seeds was achieved by priming for 72 h in a 1:25 SSE-water solution. Additionally, primed seeds stored for 12 months at room temperature in a sealed plastic bag, under dark conditions, exhibited lower electrolyte leakage and higher levels of total phenol, 2,2-diphenyl-1-picrylhydrazyl-hydrate (DPPH), and 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid (ABTS) activity, compared to non-primed seeds. The same extract, used at the same concentration, also induced early flowering and increased the number of chilli fruits per plant in comparison to the control (Dutta et al. 2019). Maize seeds soaked in 0.3, 0.5, and 0.7% solutions of SSE for one hour exhibited a higher germination potential, germination energy, and seed vigour than the control (Shanmugam and Seth 2018). The application of SSE to rice seed germination was also found to be very effective and resulted in an approximately 20% increase in overall germination. A 0.03% solution of a spray-dried powder of SSE was also effective for improved germination in pigeon pea (Karthikeyan and Shanmugam 2016a). The effect of SSEAH extracts, prepared by mixing SSE and acid hydrolysate of the carrageenan containing leftover biomass in a ratio of 25:75 or 75:25, was evaluated on the germination and growth of soybean seedlings at various concentrations.

Soybean seed priming with SSEAH improved the aerial shoot length by up to 28% and primary root length by up to 19%, as compared to the negative control (da Costa et al. 2017). Similarly, orchid seed germination was shown to be significantly improved by LSE, with treated seedlings displaying increased rooting, shoot development, and taller plantlet growth (de Araújo Amatuzzi et al. 2020) (Table 4). These findings clearly demonstrated that the bioactive compounds present in *K. alvarezii* stimulated seed germination and thus positively influenced plant growth and development.

Table 3 Bioactive ingredients and their concentrations in Minimally Processed Homogenate (MPH) of *Kappaphycus alvarezii* compared with reported studies with pure compounds applied exogenously*

Compound name	Concentrations of compounds present in 0.8% of MPH when applied as a foliar application to Tomato	Concentrations of compounds applied exogenously in reported studies	Effect of exogenous application of individual compound
Catechin hydrate	1.5 ppm	0.1 ppm	Upregulated the perception and biosynthesis of auxin hormone (Bais et al. 2010). Increased the fresh weight of *Arabidopsis thaliana* by 29% (Prithiviraj et al. 2007; Bais et al. 2010)
Naringenin	150 nM	125 nM	Had antioxidant, antifungal, antibiotic, and antimutagen effects (Sharma and Datt 2020). Promoted growth stimulating bacteria in soil (Nouwen et al. 2019)
Galactose	23.5 µM	25 µM	Impacted the phenotype of root development of *Arabidopsis thaliana*(Althammer et al. 2020). Exogenous application enhanced biofilm formation as well as IAA production in selected *Pseudomonas* spp. (Panichikkal and Edayileveetil Krishnankutty 2020)
Cinnamic acid	6.5 µM	2.5 µM	Enhanced stem length, stem diameter, fresh shoot weight and dry stem weight in *Nicotiana benthamiana* plants (Steenackers et al. 2019)
Benzoic acid	6 ppm	2 ppm	Increased photosynthetic rate, intracellular CO_2, water-use efficiency, stomatal conductance, and transpiration rate in soybean plants (Anjum et al. 2013). Induced defence response and increased the lettuce growth (Windisch et al. 2021)
Putrescine	57 µM	10 µM	Implicated in various hormonal pathways, like ABA (Alcázar et al. 2010). Had a role in osmotic adjustment (Al-Kandari et al. 2009). Increased shoot weight, root weight, and seedling weight in plants like tomato (Kundu et al. 2022), soybean (Arun et al. 2014), cucumber (Zhu and Chen 2005), *Withania somnifera* (Sivanandhan et al. 2011)
Glycine	4 ppm	5 ppm	Increased growth of coriander (Mohammadipour and Souri 2019)
Cysteine	41 µM	0.01 µM	Ameliorated injurious effects of salinity stress and increased antioxidant enzyme activities in wheat plants (Nasibi et al. 2016)
Leucine	62 µM	< 100 µM	Regulated salt tolerance in *Arabidopsis* plants (Zhao et al. 2018)
Proline	26 µM	10 µM	Alleviated the effects of abiotic stress caused by osmotic differences (Beumer et al. 1994), salt (Anamul Hoque et al. 2007; Hoque et al. 2007), chilling (Posmyk and Janas 2007), and heat (Kaushal et al. 2011)
Methionine	3 ppm	0.2 ppm	Increased leaf width, number of leaves, leaf length, plant height, root weight, and net photosynthesis parameters in lettuce plants (Khan et al. 2019)
Phenylalanine	33 µM	1–5 µM	Increased flavonoid concentration and growth of *Gardenia* plantlets (El-Ashry et al. 2019)

Table 3 (continued)

Compound name	Concentrations of compounds present in 0.8% of MPH when applied as a foliar application to Tomato	Concentrations of compounds applied exogenously in reported studies	Effect of exogenous application of individual compound
Lysine	107 μM	5–40 μM	Increased the callus formation of rice plant in tissue culture (Pongtongkam et al. 2004)
Glutamic acid	72 μM	13–130 μM	Increased the endogenous microbiota that protected plants against pathogen infection (Kim et al. 2021)
IAA	0.05 μM	0.01 μM	Enhanced levels of pigments, cell numbers and super oxide dismutase activity in the cells (Piotrowska-Niczyporuk et al. 2018)

*The assumption implied here is that the MPH complex containing the active will have the same effect as active on its own. This assumes there is no synergism or antagonism between individual chemical species within the MPH mixture

Effects on plant growth, yield, and produce quality

In 335 multi-locational and multicrop trials, the use of SSE, along with recommended fertilizer rates, resulted in an average significant yield increase in cereals (13–23.5%), pulses (14–36.9%), sugarcane (13–16.7%), potato (14–16.9%), and oilseeds (19–26.8%) when compared to the control of normal, recommended fertilizer rates (Mantri et al. 2022). The effects of *K. alvarezii* extracts on several crops, including vegetables, cereals, pulses, legumes, oil crops, flowers, fruits, and perennial grasses, are compiled in Table 4, indicating the potential benefits of these extracts at different concentrations and through various application methods.

SSE, applied at concentrations ranging from 0.5—15% of applied solution prepared in water by drench or foliar spray to different crops, significantly increased yields by 13—61% and promoted growth by enhancing height, dry matter accumulation, nutrient uptake, fruit or grain quality parameters, and root attributes (Babu and Rengasamy 2012; Singh et al. 2015b; Dwivedi et al. 2016; Deb and Singh 2022; Layek et al. 2023). SSE improved crop quality by augmenting biochemical parameters such as carbohydrate, protein, and lipid content in grains and leaves, lycopene content in fruits such as tomatoes, and oil content in groundnut (Babu and Rengasamy 2012; Karthikeyan and Shanmugam 2015; Layek et al. 2018; Pramanick et al. 2020; Chaudhari et al. 2023). In legumes, SSE was shown to increase the number of root nodules (Raverkar et al. 2016). Furthermore, it regulated genes associated with stress, defense, phytohormones, nitrogen metabolism, signal transduction, photosynthesis, ion transport, antioxidant pathways, and polysaccharide metabolism in plants such as tomato, wheat, and maize (Agarwal et al. 2016; Patel et al. 2018; Kumar et al. 2020; Trivedi et al. 2021). Additionally, a 7.5% SSE was found to reduce the required chemical fertilizer dose by 25% (Pramanick et al. 2017). SSE also contributed to a positive nitrogen balance when applied in cropping systems (Pramanick et al. 2020). Additionally, the foliar application of a 0.2% solution of AquAsap powder, which is commercially available and prepared by using SSE, resulted in a significant improvement in the total soluble solid, moisture content, ash content, and pyruvic acid, as well as the yield of onion bulbs (Karthikeyan and Shanmugam 2016b).

The performance of SSE is deemed to rely on the presence of nutrients and plant growth regulators (19.65–26.52 ppm) (Layek et al. 2015). In potato, these compounds were hypothesized to facilitate the translocation of greater amounts of photosynthates and nutrients into the tubers, leading to an increase in both the number and size of tubers (Pramanick et al. 2017). SSE also helped rice plants to take up more nutrients (Pramanick et al. 2014a) resulting in higher growth and yield. Zeatin (19.6 ppm) was found to reduce leaf drop in soybean (Lodhi et al. 2015).

For a better understanding of the mechanisms of action of SSE, diethyl ether and ethyl acetate were used to selectively eliminate IAA and GA_3 from the original SSE. The selective elimination of GA_3 from the SSE resulted in a higher photosynthetic rate and yield and increased CO_2 uptake in treated plants, as compared to those treated with basally applied SSE (Mondal et al. 2015; Layek et al. 2023). These results were hypothesized to be due to the prevention of negative interactions between GA_3 and cytokinins in this particular study. It was also reported that choline chloride and glycine betaine present in SSE were positively correlated with yield (Mondal et al. 2015). The findings suggested that each component of the extract played specific roles, which may interact either synergistically or antagonistically. The ratio of these components was the critical factor influencing their effectiveness in improving plant growth and productivity, as well as providing tolerance to various stresses.

For plantation crops such as banana, three applications of a 5% solution of the commercial form of SSE 'AquAsap' resulted in a higher yield (i.e., up to 56.6% over the control) as well as increased nutritional content (Karthikeyan and

Table 4 Summary of the extraction processes, stages and methods of application, volume or concentrations applied and effects of various extracts of the red alga *Kappaphycus alvarezii* on crop production

Crop	Extraction process	Application stage	Application method	Volume or concentration applied	Effect on crop production	References
Vegetables, Herbs and Spices:						
Tomato (*Solanum lycopersicum*)	Milling and filtered for liquid extract (SSE)	7 days before and 7 days after flowering	Foliar	2.5, 5, 7.5 and 10% of seaweed extract	Increased yield by 61% and nutrient uptake	Zodape et al. 2011
		On 20 days old seedlings	Foliar	5% seaweed extract	Differentially regulated defense related genes and phytohormone signaling	Agarwal et al. 2016
		At seedling, early vegetative, and flowering / fruiting stage	Foliar	5 and 10% seaweed extract	Increased chlorophyll index, primary branches, weight per fruit and fruit diameter	Layek et al. 2023
		At seedling, early vegetative and flowering stage	Foliar	5 and 10% seaweed extract	Improved dry matter accumulation, ascorbic acid, and lycopene content. Increased fruit yield by 31%	Layek et al. 2018
	Boiling and filtered for gel like liquid (BSE)	Applied on fruits as a coating material	Coated on fruits	1.0, 2.0 and 3.0% of seaweed extract gel	Exhibited antibacterial/fungal activity, increased quality and shelf life to 28 days of tomato fruit	Banu et al. 2020
	No details given	30 and 50 DAT*	Foliar	0.5% seaweed	Increased chlorophyll level, protein content, shoot length and nitrate reductase activity	Kavipriya and Boominathan 2018
	Minimally Processed Homogenate (MPH)	Thrice at 27 (vegetative), 53 (flowering) and 81 (fruit development stage) DAS	Foliar	0.8%	Increased yield by 31% under field capacity and 19% under drought conditions	Vaghela et al. 2023
Potato (*Solanum tuberosum*)	Milling and filtered for liquid extract (SSE)	20, 40 and 60 DAP at a volume of 600 L ha^{-1}	Foliar	2.5, 5 and 7.5% seaweed extract	Increased growth, yield (by 35%) and quality	Pramanick et al. 2017
		Twice	Foliar	2.5, 5, 6.25, 7.5 and 10% seaweed extract	Increased yield by 9%, nutrient uptake and B:C## ratio	Dwivedi et al. 2016
		At 35, 45, and 55 DAS	Foliar	2.5, 5, 6.25, 7.5 and 10% seaweed extract	Increased growth and yield (by 7%)	Prajapati et al. 2016
Okra (*Abelmoschus esculentus*)	Milling and filtered for liquid extract (SSE)	1st spray at flowering and after that every three weeks	Foliar	2.5, 5, 7.5 and 10% seaweed extract	Improved yield by 20% and nutritional quality	Zodape et al. 2008
		At seedling, early vegetative, and flowering / fruiting stage	Foliar	5 and 10% seaweed extract	Raised the number of fruit per plant and fruit length	Layek et al. 2023
French bean (*Phaseolus vulgaris*)	Milling and filtered for liquid extract (SSE)	At seedling, early vegetative, and flowering / fruiting stage	Foliar	5 and 10% seaweed extract	Increased plant height, chlorophyll index, pod length and weight per plant (by 15%)	Layek et al. 2023
Chilli (*Capsicum frutescens*)	Milling and filtered for liquid extract (SSE)	In germination study: On seeds In greenhouse study: On the day of transplantation and at 30, 60 and 90 DAT	In germination study: Seed soaking In greenhouse study: Soil drench on the day of transplantation and foliar spray at 30, 60 and 90 DAT	In germination study: 1, 2, 5 and 10% seaweed extract for 6, 12 and 24 h. In greenhouse study: 100 ml of 1, 2, 5 and 10% as soil drench and after that foliar spray at respective DAT	Increased plumule length, radicle length, fresh weight of seedlings, and yield by 23%	Babu and Rengasamy 2012
		At germination stage for seed priming	Soaked in priming solutions	Seaweed extract: water at 1:1, 1:5, 1:10, 1:25, 1:50, 1:100, 1:250, 1:500, 1:1000 dilutions for 24, 48 and 72 hs. each	Improved germination percentage, seedling weight, vigour index, and reproductive traits after priming	Dutta et al. 2019
Onion (*Allium cepa*)	Commercial AquAsap powder from AquAgri Processing Pvt Limited	4 sprays: 1st at establishment stage (10–15 DAS), 2nd, 3rd and 4th at vegetative stage (30–40 DAS), bulb formation (60–65 DAS) and bulb development stage (75–80 DAS), respectively	Foliar	0.2% of AquAsap powder	Increased bulb yield by 32% and quality parameters (i.e. soluble solid, moisture content, ash content, pyruvic acid)	Karthikeyan and Shanmugam 2016b
Saffron (*Crocus sativus*)	Milling and filtered for liquid extract (SSE)	Dipping: corm dipping oliar: 30, 45, 60, 75 days after sowing (DAS) Drenching: after 30, 45, 60, 75 days of sowing (DAS)	Dipping, Foliar, Drenching	5% seaweed extract (of 80% *Kappaphycus* + 20% *Sargassum* mixture)	Increased growth and biochemical parameters	Chaudhari et al. 2023
Cereals:						

Table 4 (continued)

Crop	Extraction process	Application stage	Application method	Volume or concentration applied	Effect on crop production	References
Maize (*Zea mays*)	Milling and filtered for liquid extract (SSE)	At 30, 50 and 70 DAP	Foliar	5.0% Gibberellic acid (GA_3) free seaweed extract	Raised yield (by 36%) and stover (by 26%) production	Mondal et al. 2015
		33, 63 and 83 DAS	Foliar	2.5, 5.0, 10 and 15% seaweed extract	Increased growth and yield (by 13%) parameters, dry matter, leaf area and nutritional quality of grains	Layek et al. 2015
		On seeds in germination study and at 20, 40 and 70 DAS in field study with and without seed treatment	Seed soaking in germination study and seed treatment along with foliar application in field study	Germination study: soaking in 0, 2.5, 5, 10, 15, 20% seaweed extract for 12 h Field study: 10 and 15% seaweed extract and seed treatment with 15% seaweed extract	Increased germination rate, plant dry weight, and yield in a concentration dependent manner (maximum up to 21%)	Dilavarnaik et al. 2017
		at knee high stage (25–30 DAS, tasseling stage (50–55 DAS) and silking stage (70–75 DAS)	Foliar	2.5, 5.0, 7.5, 10 and 15% seaweed extract	Increased plant height, dry matter, chlorophyll content, yield (by17%), and micronutrient (Cu, Zn, Mn, Fe) content in grains	Layek et al. 2019
		At knee high stage (30 DAS), tasselling stage (50 DAS) and grain formation stage (70 DAS)	Foliar	2.5, 5.0, 7.5, 10 and 15% seaweed extract	Increased nutrient uptake and yield (by 34%)	Singh et al. 2015b
		on the foliage of maize thrice at 20 days interval starting from 30DAS till 70 DAS	Foliar	2.5, 5.0, 7.5, 10 and 15% seaweed extract	Increase yield (by 34%) and B:C ratio and net return	Singh et al. 2015a
		At V3, V5, V10, V15 and grain filling stages	Foliar	10% seaweed extract	Increased growth and yield (by 32%) at specific growth stages	Trivedi et al. 2017
		At V5 stage (30 DAS)	Soil drench	2.5% seaweed extract in a volume of 2 L irrigation water	Upregulated genes involved in root growth, gibberellic acid and auxin signaling, seed development, nitrogen metabolism, and antioxidant activity. Down regulated genes involved in sucrose and starch degradation. Increased root growth, yield (by 31%) and nutrition level in the roots of drought stressed plants	Kumar et al. 2020
		25, 59 and 78 DAS	Foliar	10 and 15% seaweed extract	Improved antioxidant enzyme levels, decreased MDA content, and imparted drought tolerance	Trivedi et al. 2018b
		On seeds	Seed soaking	Soaked for 1 h. in 0.3, 0.5 and 0.7% solutions	Improved germination	Shanmugam and Seth 2018
		At 30, 50 and 70 DAS	Foliar	2.5, 5.0, 7.5, 10 and 15% seaweed extract at a volume of 500 L ha^{-1} in 1st spray and 700 L ha^{-1} in 2nd and 3rd spray	Increased growth, yield (by 21%) and nutritional quality. Reduced the requirement of chemical fertilizers	Singh et al. 2015c
		At 30, 50 and 70 DAS	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract	Increased growth, yield (by 34%) and B:C ratio	(Pal et al. 2015b)
		In germination study: On seeds In field study: seed treatment and/or 20 40 and 70 DAS	In germination study: Seed soaking for 12 h. In field study: seed treatment and/or foliar spray	In germination study: 2.5, 5, 10, 15, and 20% seaweed extract In field study: seed treatments (with 15% extract) along with foliar spray of 10 and 15% seaweed extracts	Increased germination and yield (by 12%)	Basavaraja et al. 2018
		At grain filling stage	Foliar	10% seaweed extract	Increased yield under irrigated conditions by 33%, but not under drought conditions. Improved antioxidant enzymes and decreased ROS#	Trivedi et al. 2018a
		At V5, V10, and V15 stages	Foliar	10% seaweed extract	Improved yield dependent on timing of application. Elevated levels of antioxidant enzymes	Trivedi et al. 2022a
		At V5 stage	Foliar	10% seaweed extract	Up-regulated genes involved in nitrate transportation, photosynthesis, signal transmission, and glycogen and starch biosynthetic processes. Down-regulated genes involved in the catabolism of polysaccharide molecules such as starch and chitin	Trivedi et al. 2021
		At V5, V10, and V15 stages	Foliar	10% seaweed extract	Changed soil bacterial communities	Trivedi et al. 2022b

Table 4 (continued)

Crop	Extraction process	Application stage	Application method	Volume or concentration applied	Effect on crop production	References
Rice (*Oryza sativa*)	Milling and filtered for liquid extract (SSE)	Three sprays (Time of application not given)	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract	Increased grain and straw yield (by 41%), and nutrient uptake	Pramanick et al. 2014b
		35, 45, and 60 DAT	Foliar	2.5, 5, 7.5, 10, and 15% seaweed extract	Increased chlorophyll content, quality, growth and yield (by 12%)	Devi and Mani 2015
		In germination study: On seeds In greenhouse study: On the day of transplantation and at 30, 50 and 70 DAT	In germination study: Seed soaking In greenhouse study: Soil drench on the day of transplantation and foliar spray at 30, 50 and 70 DAT	In germination study: 1, 2, 5 and 10% seaweed extract for 6, 12 and 24 h. In greenhouse study: 100 ml of 1, 2, 5 and 10% as soil drench and after that foliar spray at respective DAT	Increased plumule and radicle length, seedling weight chlorophyll, protein, carbohydrate, lipid contents and yield (27%)	Babu and Rengasamy 2012
		In germination study: on seeds In field study: at vegetative stage (25–30 DAT, second at tillering stage (50–55 DAT) and third at flowering stage (70–75 DAT)	In germination study: soaking for 24 h. In field study: Foliar	In germination study: 2.5, 5, 7.5, 10, and 15% seaweed extract In field study: 2.5, 5, 10, and 15% seaweed extract	Increased germination, growth, yield (by 15%) and micronutrients and protein in grains	Layek et al. 2017
		At 35, 60 and 70 DAT	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract at a volume of 500–600 L ha^{-1}	Increased yield (by 32%) and nutrient uptake	Pal et al. 2015a
	Bioformulations of *K. alvarezii* (SSEAH)	Three sprays (Time of application not given)	Foliar	1.0 and 2.0 ml L^{-1} with different combination of fungicides	Increased chlorophyll content	Banakar and Kumar 2020
		On 30 days old plants	Foliar	20% LBS-6 – 1.0 ml/L and 20% LBD1 – 2.0 ml L^{-1}	Maintained stomatal opening and leaf temperature in fungicide induced stress, decrease ROS and stress responsive genes in treated plants	Banakar et al. 2022
		On 3 week old plants	Foliar and root dipping	For foliar: LBS-6 – 1.0 ml L^{-1} and LBD1 – 2.0 ml L^{-1} with/without *Magnaporthe oryzae* isolate For root dipping: LBD1 1.0 and 2.0 ml L^{-1} Combine: LBD1 1.0 ml L^{-1} foliar and 2.0 ml L^{-1} by root dipping	Induced defense related genes, provided defense against fungus infection, increased level of phenylalanine ammonia lyase, chitinase, peroxidase, polyphenol oxidase and phenolic content,	Sahana et al. 2022
	Bioformulations from *K. alvarezii* (SSEAH)	On 4–4.5 week old plants	Foliar	LBD3 – 4 ml L^{-1} and LBD12 – 1 ml L^{-1} at 24 or 48 h before bacterial infection	Provided anti-bacterial defense	Roy et al. 2022
Wheat (*Triticum aestivum*)	Milling and filtered for liquid extract (SSE)	On 25 Days old seedlings	Foliar	7.5% seaweed extract	Increased number of grains per plant by 47%, provided salt and drought tolerance, reduced cell membrane damage, electrolyte leakage, MDA### content and ROS levels. Increased the level of osmoprotectants. Regulated phytohormones and stress responsive genes	Patel et al. 2018
		At vegetative, tillering and grain filling stage	Foliar	2.5, 5.0, 7.5 and 10% seaweed extract	Increased yield (by 20%) and nutrient content	Shah et al. 2013
		At vegetative, tillering and grain filling stages	Foliar	0.25, 0.5 and 1.0%	Increased yield, protein, carbohydrates and growth	Zodape et al. 2012
Rice-Potato-Green gram crop system	Milling and filtered for liquid extract (SSE)	In rice: at 20, 40 and 60 DAT In Potato: at 20, 40 and 60 DAP** In green gram: 20 and 40 DAS***	Foliar	2.5, 5.0, and 7.5% seaweed extract at a volume of 500 L ha^{-1}	Increased physical quality parameters, amylose, carbohydrate and yield of rice by 32%. Increased positive nitrogen balance in the system	Pramanick et al. 2020
		In rice: at 20, 40 and 60 DAT In potato: at 15, 30, 45 DAP In green gram: 20 and 40 DAS	Foliar	2.5, 5.0, 10 and 15% seaweed extract at a volume of 650 L ha^{-1}	Increased growth, yield (by 41%) and nutritional quality of rice	Pramanick et al. 2014b
Rice-Potato-Black gram crop system	Milling and filtered for liquid extract (SSE)	-	Foliar	2.5, 5.0, 10 and 15% seaweed extract	Increased growth, yield (by 33, 35, and 57% in rice, potato, and Black gram, respectively), nutrient uptake and economics of the crop	Pramanick et al. 2018

Table 4 (continued)

Crop	Extraction process	Application stage	Application method	Volume or concentration applied	Effect on crop production	References
Maize-Garden pea crop system	Milling and filtered for liquid extract (SSE)	Not given	Foliar	5 and 10% seaweed extract	Increased growth and yield (by 33, and 19 in maize and Garden pea, respectively) in both the crops	Garai et al. 2019
Pulses and Legumes:						
Black gram (*Vigna mungo*)	Milling and filtered for liquid extract (SSE)	At seedling stage (25 DAS) and pre flowering stage (50 DAS)	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract	Increased growth, and yield (by 51%)	Pramanick et al. 2016
		40 and 52 DAS	Foliar	2.5, 5, 10 and 15% seaweed extract at a volume of 500 L ha^{-1}	Increased growth, yield (by 48%) and nutritional quality	Jadhao et al. 2015
		At 30 and 50 DAS	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract at volume of 500 L ha^{-1}	Increased growth, yield (by 49%), nutrient uptake, and B:C ratio	Dwivedi et al. 2014
		At vegetative stage (20–25 DAS) and flowering stage (35–40 DAS)	Foliar	5, 10, and 15%	Increased protein yield, vigour index, macro and micro nutrients	Mahajan et al. 2017
Green gram (*Vigna radiate*)	Milling and filtered for liquid extract (SSE)	20 and 40 DAS	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract	Increased nutrient uptake, grain and straw yield	Pramanick et al. 2013
		25 and 50 DAS	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract	Increased yield (by 34%) and nutritional quality	Raverkar et al. 2016
		At flowering stage	Foliar	5.0, 10 and 15%	Improved yield (by 30%) and nutrition	Zodape et al. 2010
		At 27, 45, and 60 DAS	Foliar	2, 4, and 6%	Improved nitrogen uptake	Akhila et al. 2017
		At 30 and 50 DAS	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract at volume of 500 L ha^{-1}	Increased growth, yield, nutrient uptake and B:C ratio	Dwivedi and Ashok 2015
	Used a patented product (mixture of two algal species including *K. alvarezii* and also biofertilizers)	Seed soaked before germination and foliar at 25 and 35 DAS	Seed soaking and foliar	For seed soaking 0.1% solution for 30 min and for foliar 0.25% solution of seaweed extract	Increased plant and root growth, chlorophyll content of leaves, yield (by 26%), and nutrients	Iswarya et al. 2019
Red gram (*Cajanus cajan*)	Commercial powder from AquAgri Processing Pvt Limited	Germination phase, vegetative stage, pre-flowering stage and pod maturity stage	Seed soaking for 1 h in germination study. Foliar for field study	0.03% of *K. alvarezii* powder solution for germination testing and 0.2% for field study	Increased germination and yield (by 36%)	Karthikeyan and Shanmugam 2016a
Oil crops:						
Soybean (*Glycine max*)	Milling and filtered for liquid extract (SSE)	At seedling stage (30 DAS) and at flowering stage (60 DAS)	Foliar	2.5, 5, 7.5, 10, 12.5 and 15% seaweed extract at a volume of 650 L ha^{-1}	Increased growth, yield (by 57%) and nutrient uptake	Rathore et al. 2009
		At 25, 50 and 75 DAS	Foliar	2.5, 5, 7.5, 10 and 15% seaweed extract	Improved growth, yield (by 58%) and flowering behavior	Lodhi et al. 2015
	Bioformulations of *K. alvarezii* (SSEAH)	Before germination as a seed primer	On seeds as per given doses	100% SSE and mixture of SSE and carrageenan containing acid hydrolyzates in a ratio of 1:3 or 3:1. Doses were 2.5, 4, 5, 8 ml 100 kg^{-1} seeds	Increased length of aerial parts and root of seedlings	da Costa et al. 2017
Groundnut (*Arachis hypogaea*)	Milling and filtered for liquid extract (SSE)	In germination study: On seeds In greenhouse study: On the day of transplantation and at 30, 45 and 60 DAT	In germination study: Seed soaking In greenhouse study: Soil drench on the day of transplantation and foliar spray at 30, 45 and 60 DAT	In germination study: 1, 2, 5 and 10% seaweed extract for 6, 12 and 24 h. In greenhouse study: 100 ml of 1, 2, 5 and 10% as soil drench and after that foliar spray at respective DAT	Increased plumule, and radicle length, seedling weight biochemical parameters, and yield by 31%	Babu and Rengasamy 2012
	Commercially available AquAsap from AquAgri Processing Pvt Limited	Vegetative stage, pod developing stage and at maturity stage	Foliar	0.5% thee times; at 25, 45 and 60 DAS	Increased growth, yield (by 32%) and oil content (by 14%)	Karthikeyan and Shanmugam 2015
Sesame (*Sesamum indicum*)	Milling and filtered for liquid extract (SSE)	At 30, 40, and 50 DAS	Foliar	5, 7.5, 10, 15% with 100% RDF and 7.5% with 75% and 100% RDF 600 L ha^{-1} volume	Improved growth, yield (by 73%) and economics	Shankar et al. 2020
Flowers:						

Table 4 (continued)

Crop	Extraction process	Application stage	Application method	Volume or concentration applied	Effect on crop production	References
Orchids (Orchidaceae)	Lyophilized powder of whole seaweed used at 1 g 10 ml^{-1} concentration and again lyophilized before application (LSE)	Germination stage	In a culture media as per different concentrations given	0, 6, 12, 25, 50 and 100 mg L^{-1}	Increased rooting, shooting, development of plantlets and high fresh mass 50 mg L^{-1}	de Araújo Amatuzzi et al. 2020
Fruits:						
Banana (*Musa*)	Commercially available AquAsap from AquAgri Processing Pvt Limited	At 3rd, 5th and 7th month of plantation	Foliar	5% of AquAsap solution	Improved yield (by 32%) and nutritional content	Karthikeyan and Shanmugam 2014
Kiwifruit (*Actinidia deliciosa*)	Not given	Base dipping at cuttings stage and drench every 15 days	Base dipping of cuttings and drench	1, 5, 10, and 50% of seaweed extract at base dipping of cuttings for 6 h and drenching of 50 ml solution of same concentrations every 15 days for six months	Increased root parameters, pigments, metabolites and decreased electrolyte leakage,	Dutta et al. 2023
Perennial grass:						
Sugarcane (*Saccharum officinarum*)	Milling and filtered for liquid extract (SSE)	At germination (30th day), at tiller sprouting stage (75th day), at sugar building stage (125th day)	Foliar	1% solution	Increased yield (by 25%), brix, purity, and polarity	Karthikeyan and Shanmugam 2017
		At 60 (early formative), 90 (late formative) and 120 days after planting (grand growth stage)	Foliar	2.5, 5, 7.5, and 10% seaweed extract with 100% RRF### and 6.25% seaweed extract with 50% RRF### with spray volume of 800 L ha^{-1}	Improved germination, tillers per plant, plant height, leaf area index, dry matter accumulation, crop growth rate, yield (by 10%) and economics. Had significant saving in CO_2 emission	Singh et al. 2018
Medicinal plants:						
Withania somnifera	commercially available seaweed extract powder of *Kappaphycus alvarezii* with the trade name'Magic vita—P'	To 31 days old *Withania somnifera* shoot cultures	Added to solid Murashige-Skoog media	0.15, 0.25. 0.50, 1 and 2% of seaweed powder for 6 h, 12 h, 24 h, 48 h, 7 days and 14 days	Increased biomass and withaferin A content	Vinod et al. 2022
Ocimum basilicum L	Milling and filtered for liquid extract (SSE) under brand name "sagarika"	at vegetative (15 DAT) and flower initiation stage (40 DAT)	Foliar	7 ml L^{-1}	Increased photosynthetic rate, content of methyl chavicol and linalool	Raj et al. 2022

SSE Strained Seaweed Extract, *BSE* Boiled Seaweed Extract, *LSE* Lyophilized Seaweed Extract, *SSEAH* Strained Seaweed Extract cum Acid Hydrolysate

*DAT = Days after transplanting

**DAP = Days after planting

***DAS = Days after sowing

#ROS = Reactive oxygen species

##B:C ratio = Benefit: Cost ratio

###RRF = Recommended rate of chemical fertilizer

Shanmugam 2014). Sugarcane plants treated with a 1% SSE of that proprietary extract had a higher sugar brix, purity and polarity (Karthikeyan and Shanmugam 2017). In sugarcane, SSE (5%) applied three times as a foliar spray increased productivity by 12.5% and reduced chemical fertilizer use. A life-cycle impact assessment indicated a positive sustainability impact, with 5% SSE having the highest reduction in greenhouse gas emissions (260 kg CO_2 equivalent ha^{-1}) (Singh et al. 2018). Sharma et al. (2017) have reported a 11.4% reduction in climate change impact category while using SSE at 15% in rice. Further they also showed that at least 35 kg CO_2 equivalents per tonne of rice could be saved while using SSE with 50% recommended rate of fertilizers.

A bio-formulation (i.e. LBS6) prepared using SSEAH of *K. alvarezii* was found to increase the chlorophyll content of rice leaves when treated three times at a concentration of 1 mL L^{-1} (Banakar and Kumar 2020). The bioactive compounds present in LBS6 induced the expansion of cucumber cotyledons by regulating the expression of the genes involved in cell division, expansion and proliferation and phytohormone metabolism (Shukla et al. 2023). Additionally, LBS6-treated cotyledons differentially modulated carbohydrate metabolism to provide energy to expanding cotyledons (Shukla et al. 2023). The same study showed that the foliar spray of LBS6 regulated photosynthesis and improved plant growth with higher foliage growth (Shukla et al. 2023). Similarly, de Castro et al. (2023) showed that the organic fragments of κ-Cg, lipids and peptides present in an aqueous extract of *K. alvarezii,* enriched with a potassium-rich inorganic fraction from *K. alvarezii,* improved the growth and nutrient-uptake-efficiency of rice. Furthermore, the application of 0.8% MPH on tomato plants was found to increase the yield by 31% under normal conditions and by 19% under drought conditions, in comparison to the control groups. The applied solution of 0.8% contained several physiologically relevant bioactive compounds as detailed in the section "Components of *Kappaphycus alvarezii* and their activities" (Vaghela et al. 2023). In another experiment, coating tomato fruits with 1, 2, and 3% concentrations of BSE was found to exhibit anti-bacterial and anti-fungal properties, ultimately resulting in enhanced quality and prolonged shelf-life of tomato fruits by up to 28 days (Banu et al. 2020).

Soaking greengram seeds in a 0.1% solution in water for 30 min, followed by two foliar sprays on the crop at 25 and 35 days after sowing, using a 0.25% solution containing a mixture of *K. alvarezii* (red alga), *Sargassum* sp. (brown alga), and select, microbial bio-fertilizers (e.g., *Rhizobium*, *Azotobacter*, *Acetobacter*, phosphorus-solubilizing bacteria, and potassium-mobilizing bacteria) resulted in improved plant and root growth, increased leaf chlorophyll content, higher grain yield, and enhanced nutrient levels in the grains (Iswarya et al. 2019).

Stress resilience

Given the variability in climate conditions, seaweed biostimulants enable and prime crops to endure and even thrive under unfavorable environmental circumstances. In general, seaweed extracts help plants achieve this through various strategies, such as improving nutrient-uptake-efficiency (NUE), enhancing root growth, and activating stress-responsive genes. Several studies reported on the ability of *K. alvarezii*-based extracts to provide tolerance to plants against both abiotic and biotic stressors and improve the growth, yield, and nutritional quality of various crops. For instance, 10% and 15% SSE increased drought stress tolerance in maize, when applied three times (i.e., at 25, 59, and 78 days after sowing) by elevating antioxidant enzyme activity, such as catalase, ascorbate peroxidase, glutathione reductase, and superoxide dismutase, and reducing malondialdehyde (MDA) and reactive oxidant species levels. These concentrations of SSE also purportedly protected cell organelles, chlorophyll, and macromolecules during stress conditions (Trivedi et al. 2018a). Alleviation of moderate soil moisture stress in maize was achieved with 10% SSE, while a higher concentration (15%) was required for an alleviatory response to severe stress at the V5 or V15 stages (Trivedi et al. 2018a). These studies contributed significantly to a better understanding of all extracts of seaweed, highlighting the importance of a dose dependent, stress alleviation responses in plants generally.

In another study, foliar application of 10% SSE, carried out only once, at the grain filling stage of maize increased growth and yield under normally irrigated conditions, but not under drought stress conditions. Here, the authors proposed that the quaternary ammonium compounds and other bioactive compounds present in the SSE might have assisted the plants in tolerating soil moisture stress during brief dry spells (Trivedi et al. 2018b). Similarly, maize yield was enhanced up to 31.5% under drought-stressed conditions and up to 20.4% under well-watered conditions through drench application of 2.5% SSE (Kumar et al. 2020).

Plants experience negative effects on their chlorophyll and carotenoid contents due to drought and salinity stress. Applying 7.5% SSE to 25-day-old wheat seedlings significantly increased photosynthetic pigment concentrations, providing relief from both drought and salt stress (Patel et al. 2018). *Kappaphycus* extract-treated wheat plants were found to have the highest internal levels of the plant hormones cytokinin and ABA, known to be involved in protecting photosynthetic pigments during stressful conditions (Rivero et al. 2009). Patel et al. (2018) reported that after applying 7.5% SSE, reactive oxygen species (ROS) levels were reduced, along with lower lipid peroxidation and electrolyte leakage. Salinity stress impairs the Na^+/K^+ ratio in leaves (Shukla et al. 2015), which hampers transpiration due to stomatal guard cell effects and negatively affects ion transporter activity (Patel et al. 2018). SSE helped maintain a balanced Na^+/K^+ ratio and a higher Ca^{++} ion content, which together provided an improved osmotic balance to treated plants under abiotic stress conditions. It also maintained the turgor pressure of cells in treated plants, reducing extreme water loss under stressful conditions and reducing damage to various cell membranes. Applying the extract on wheat triggered the levels of many other osmo-protectants, suggesting its role in osmotic balance and stress tolerance. Upon application of the extract to wheat plants, stress-responsive genes such as *WCK-1* and the wheat-specific mitogen-activated protein (MAP) kinase gene were upregulated. *WCK-1* was reported to increase up to 1.2 – 1.4-fold higher in salt- and drought-stressed wheat plants when treated with SSE. These MAP kinase cascade genes play significant roles in the regulation of cellular processes under normal and abiotic stress conditions (Patel et al. 2018).

Role in plant defence against biotic stress

κ-Cg can prime and elicit plant defence mechanisms (Vera et al. 2011; Shukla et al. 2016; Paulert and Stadnik 2019). Specifically, κ-Cg has been found to increase the activity of phenylalanine ammonia-lyase, leading to the production of antimicrobial phenylpropanoid compounds that can protect tobacco plants against various pathogens such as tobacco mosaic virus (TMV), *Botrytis cinerea,* and *Pectobacterium carotovorum* (Vera et al. 2012). Additionally, carrageenans and oligo-carrageenans, which contain κ-Cg, have been shown to modulate the salicylate, jasmonate, and ethylene signalling pathways, eliciting plant defence responses against a range of pathogens, including viruses, bacteria, viroids, fungi, and insects (Shukla et al. 2016). A 5% SSE was found to regulate plant hormones and defence-related genes in tomato plants related to alleviating biotic stress due to infection by the fungus *Macrophomina phaseolina*, a causative agent of charcoal rot disease (Agarwal et al. 2016). Thus, *Kappaphycus*-based, carrageenan-containing biostimulants can support the induction of systemic resistance in plants against different pathogens. They increase the endogenous levels of abscisic, indole acetic and salicylic acids (ABA, IAA and salicylic acid (SA), respectively) and zeatin. Up-regulation of some defense-related genes, such as *PR-1b1*, *PR-3*, and *PR-5*, and the transcription factor *Pti4* to alleviate biotic stress caused by *M. phaseolina* was also demonstrated. Elevated endogenous phytohormone levels in plants were hypothesized to be due to their presence either in extracts or due to increased endogenous biosynthesis in treated plants (Agarwal et al. 2016). It was demonstrated that the *Pti4* transcription factor participated in the enhancement of *LeMPK2*, one of the components of MAP kinase cascade proteins, responsible for Pto-mediated resistance in tomato plants and provided mitigation towards applied biotic stress (Pedley and Martin 2004; Agarwal et al. 2016). Similarly, Sahana et al. (2022) showed that a formulation (i.e., LBD1) rich in fractions of bioactive sulfated galacto-oligosaccharides (SSEAH), elicited immunity of rice against *Magnaporthe oryzae* by regulating the expression of defence-related genes and enzymes. LBD1 induced immunity in rice by up-regulating the transcription of defense-related genes (Banakar et al. 2023). Interestingly, LBD1 showed up-regulation of beta-D-xylosidase, a gene involved in secondary cell wall formation (Banakar et al. 2023). Roy et al. (2022) deciphered the mode of action of Tomatough® (LBD3) and AgFort® (LBD12), a commercial formulation of Sea6 Energy Private Limited as prepared using SSEAH (Girish et al. 2020), which elicited a systemic immune response in *Arabidopsis thaliana* and *Oryza sativa* against *Pseudomonas syringae* pv. *tomato* (PstDC3000) and *Xanthomonas oryzae* pv. *oryzae,* respectively. Tomatough® and AgFort®-treated plants showed a higher abundance of transcripts of disease-related genes and higher accumulation of SA. The expression of *FLG22-induced receptor-like kinase 1 (FRK1)* and *PR1a* genes involved in SA-mediated signalling pathways was significantly up-regulated in the treated plants. In addition, SA, ABA, IAA, and *trans*-zeatin levels were higher in Tomatough®- and AgFort®-treated plants, suggesting induced response cross-talk between different phytohormone signalling pathways to induce innate immunity in plants (Roy et al. 2022). The *K. alvarezii*-derived commercial formulation Biostimul® enriched with amino acids improved the chlorophyll content and stimulated defense against powdery mildew in lettuce (Rover et al. 2022).

Effects on root physiology and soil properties

Various seaweed extracts can have significant impacts on belowground microbial ecosystems due to their ability to improve root growth and stimulate beneficial microbiome activity, which in turn secrete beneficial secondary compounds. This, in turn, can improve nutrient cycling and overall soil health, leading to higher crop productivity. SSE has been reported to stimulate root growth when applied as a soil drench in maize plants (Kumar et al. 2020). A soil application of 2.5% SSE, at the V5 stage of maize, caused up-regulation of genes involved in root growth, GA_3 and IAA signalling, seed development, nitrogen metabolism, and antioxidant activity. The nitrogen, phosphorus and magnesium contents in SSE-treated roots of maize were improved by the extract applied under field capacity, as well as drought-stressed conditions (Kumar et al. 2020). Higher root length and volume were reported in treated maize under drought stress, which ensured better nutrient uptake and transport. Uptake of nitrogen, phosphorus, copper and iron, by the

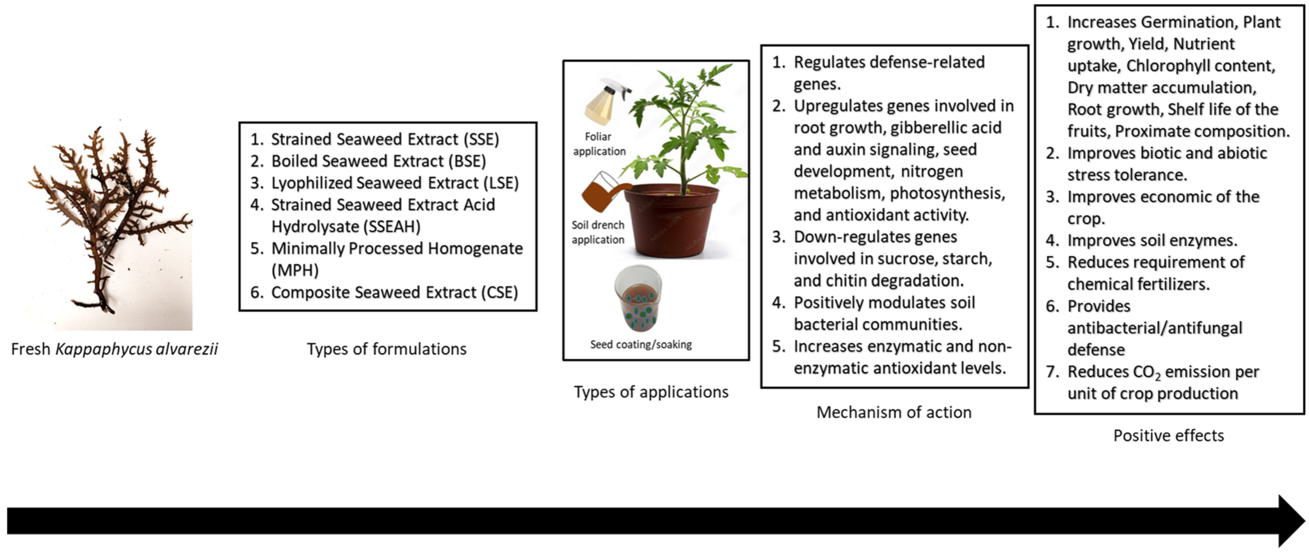

Fig. 3 All positive effects of the *Kappaphycus*-derived formulations on plants as well as the current known mechanism behind these effects

treated roots, was enhanced due to the application. Better nitrate reductase, a rate-limiting enzyme for protein metabolism, was reported in the roots of treated maize and was found to be responsible for more efficient nitrogen assimilation. It is important to note that the SSE, when applied at the effective dose, does not contain enough nutrients to meet the crop's demands. Therefore, the best results are obtained when the soil already contains sufficient amounts of macro- and micronutrients or has sufficient fertilizers applied. The possibility of reduced nutrient requirements upon application of SSE is due to the higher efficiency of nutrient uptake and assimilation, as evident in the case of nitrogen. Kumar et al. (2020) also reported increased expression of the cysteine synthase gene in SSE-treated roots under drought, which is key to producing reduced and oxidized forms of glutathione, GSH and GSSG, respectively. These antioxidants are required for quenching ROS generated during stress conditions. Key enzymes in plants responsible for fatty acid synthesis were also found to be up-regulated in treated plants. SSE modulated starch metabolism in maize roots by positively regulating the expression of genes involved in biosynthesis and negatively regulating the expression of genes involved in degradation (Kumar et al. 2020). These observations suggest that the application of SSE to plants might have a positive effect on enhancing carbohydrate storage and partitioning, leading to an increase in maize grain yield. Modulations in the genes of treated plants were related to enhanced cell wall synthesis that could lead to protection against osmotic imbalances during water shortage (Kumar et al. 2020). The presence of IAA, at approximately 21.1 ppm in the SSE may have contributed to the promotion of root growth in potato plants, ultimately increasing their nutrient uptake capacity and water-use-efficiency (Pramanick et al. 2017).

Foliar applications of SSE, applied at 10%, not only improved maize productivity under soil moisture stress conditions but also had a favourable influence on the soil bacterial community (Trivedi et al. 2022b). Under soil-moisture stress, imposed at the V5, 10, and 15 stages of maize, there was a decreased abundance (by 49–79%) of the genera *Alicyclobacillus, Anaerolinea, Bacillus, Balneimonas, Nitrospira, Rubrobacter*, and *Steroidobacter* compared to the irrigated control. However, the application of SSE improved the abundance of these soil bacteria. Several bacterial genera, e.g., *Flavobacterium*, *Nitrosomonas*, *Nitrosovibrio*, and *Rubrobacter,* which are known to be positively related to plant growth promotion and nutrient cycling, were also reported to be enriched by run-off from the extract. The SSE of *K. alvarezii* also showed favourable effects on the activities of soil enzymes. The application of SSE led to significantly higher activities of alkaline and acid phosphomonoesterases, aryl sulfatase, glucosidase, and fluorescein diacetate (FDA) hydrolysis in comparison to the control (Trivedi et al. 2022b).

Figure 3 summarises the positive effects of the *Kappaphycus*-derived formulations on plants as well as the current known mechanism behind these effects.

Research gaps and the way forward

The current literature review on a variety of *Kappaphycus alvarezii* extracts has highlighted their potential to significantly enhance crop productivity, quality, and soil properties, both under conditions for optimal growth and abiotic or biotic stresses. Many of the reviewed studies are supported by positive findings on the active ingredients and underlying mechanisms that contribute to these beneficial effects on crop productivity. Despite this, there are key research gaps that require further investigation to fully understand and optimize the use of *K. alvarezii* extracts in agriculture.

It is important to note that significant variations in the application timings, dosages, and frequencies of *K. alvarezii* extracts have been reported. There is a need for standardization of treatments across experiments, or else a justification for why such non-standard treatments were applied. Since reports suggest that this group of red seaweed extracts can alleviate biotic stress, a systematic comparison with commercial pesticides is lacking and should be pursued with vigour, since the needs in agriculture are great.

One common feature of contention is that few of these studies have reported the levels of soluble solids in their extracts, which makes it difficult, if not impossible to compare results across different formulations (liquid to powder). Sometimes the citation of a percent solution really does not mean anything, as the percentage is dependent on the processing, which is itself a major variable. This factor may primarily explain the variations in responses observed across the studies. To account for such variations, it is advisable to present the outcomes of diverse extracts on a dry weight, soluble solids basis. As extraction techniques vary, the constituents within the *K. alvarezii* extracts also differ and that may be a considerable variation that needs to be standardised. This criticism could be applied to virtually all types of extracts of all types of seaweeds. Identification of the active constituents within the extracts and their specific roles in plant metabolism should be investigated to ascertain the application doses at which they are physiologically relevant. One has to acknowledge that it is not a simple relationship to presence and concentration but with some compounds, the plants respond to various ratios of constituents. It is equally important to identify whether the active constituents produce the same effect when present in a mixture. This aspect should be carefully examined to determine if the presence of other components in the mixture influence the overall effects of the active constituent. By investigating this, we can gain a deeper understanding of how the interaction between extracts of seaweeds may affect the desired outcome or efficacy within the targeted plants they are applied to.

Information is also completely lacking on the proportion of the applied active ingredients that are absorbed by the plants and the mechanism of their uptake through foliage or roots. The interaction of seaweed extracts/formulations with the soil and leaf microbiome is yet another, largely unexplored area that is important because it can influence the production of secondary metabolites by microbes, which may affect plant growth and health. Similarly, the composition of *K. alvarezii* extracts, even though of tropical origin, are highly likely to vary over season and location; thus, it would be necessary to understand how crops respond to these variations. Such a study would also be important to generate data towards standardization of specifications of *Kappaphycus*-based biostimulants, which is currently an area of limited understanding.

Overall, this review shows that *Kappaphycus* extracts play a role in improving plant resilience to stress and therefore could be considered as an adaptive strategy for crops to environmental variability under climate change scenarios.

Conclusions

In conclusion, *Kappaphycus alvarezii*, a red macroalga known principally for its hydrocolloid content, is increasingly being used in the agriculture sector for its biostimulatory effects on crops. Various *K. alvarezii*-based well-characterized commercial products are available on the market, globally and their chemical composition and modes of application have been extensively studied. The bioactive compounds in *K. alvarezii* extracts have been shown to positively influence plant growth and development, including seed germination, nutrient uptake, dry matter accumulation, photosynthetic efficiency, and modulation of gene expression. This collective of seaweed-derived compounds can also impart tolerance against biotic and abiotic stresses. Additionally, the use of these sustainably produced red seaweed-based products can help increase soil health and reduce the need for chemical fertilizers, leading to better yields and higher quality crops. All the literature reviewed shows no negative effects of *Kappaphycus*-extracts on the yield or growth of crops, thus allaying any such concerns. However, further studies are needed to fully characterize these extracts and optimize their efficacy, including the identification of individual active compounds, the comparison of extraction methods, and the standardization of application rates and timings. Extracts of *K. alvarezii* have the potential to contribute to sustainable and economically viable agriculture, which is increasingly under considerable pressure to perform for the benefits of society.

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Declarations

Competing interests The authors declare that they do not have any competing interests.

References

Agarwal P, Patel K, Das AK, Ghosh A, Agarwal PK (2016) Insights into the role of seaweed *Kappaphycus alvarezii* sap towards phytohormone signalling and regulating defence responsive genes in *Lycopersicon esculentum*. J Appl Phycol 28:2529–2537

Al-Kandari M, Redha A, Suleman P (2009) Polyamine accumulation and osmotic adjustment as adaptive responses to water and salinity stress in *Conocarpus lancifolius*. Funct Plant Sci Biotech 3:42–48

Alcázar R, Altabella T, Marco F, Bortolotti C, Reymond M, Koncz C, Carrasco P, Tiburcio AF (2010) Polyamines: molecules with regulatory functions in plant abiotic stress tolerance. Planta 231:1237–1249

Althammer M, Blöchl C, Reischl R, Huber CG, Tenhaken R (2020) Phosphoglucomutase is not the target for galactose toxicity in plants. Front Plant Sci 11:167

Akhila K, Kaswala AR, Priyanka DP (2017) Effect of liquid fertilizers on nutrient uptake and soil properties of the green gram (V*igna radiata*) crop under organic farming. Pharma Innov J 6:224–228

Anamul Hoque M, Okuma E, Nasrin Akhter Banu M, Nakamura Y, Shimoishi Y, Murata Y (2007) Exogenous proline mitigates the detrimental effects of salt stress more than exogenous betaine by increasing antioxidant enzyme activities. J Plant Physiol 164:553–561

Anjum SA, Xue L, Wang L, Saleem MF, Huang CJ (2013) Exogenous benzoic acid (BZA) treatment can induce drought tolerance in soybean plants by improving gas-exchange and chlorophyll contents. Aust J Crop Sci 7:555–560

Annual Report (2021–22) I.F.F.C.O. New Delhi. https://iffco-public-assets.s3.ap-south-1.amazonaws.com/s3fs-public/2022-06/IFFCO_Annual_Report_2021-22.pdf?VersionId=jJfCkRc5Yl3_UdWfqzV.5s8GvKqOWOxZ; accessed 31 October 2022

Araújo PG, Nardelli AE, Duran R, Pereira MS, Gelli VC, Mandalka A, Eisner P, Fujii MT, Chow F (2022) Seasonal variation of nutritional and antioxidant properties of different *Kappaphycus alvarezii* strains (Rhodophyta) farmed in Brazil. J Appl Phycol 34:1677–1691

Arun M, Subramanyam K, Theboral J, Ganapathi A, Manickavasagam M (2014) Optimized shoot regeneration for Indian soybean: the influence of exogenous polyamines. Plant Cell Tissue Organ Cult 117:305–309

Babu S, Rengasamy R (2012) Effect of *Kappaphycus alvarezii* SLF treatment on seed germination, growth and development of seedling in some crop plants. J Acad Indust Res 1:186–195

Bais HP, Venkatachalam L, Biedrzycki ML (2010) Stimul Inhib Plant Signal Behav 5:239–246

Banakar SN, Kumar MP (2020) Foliar application of red seaweed (*Kappaphycus alvarezii*) bioformulations increased the levels of chlorophyll content in rice. J Pharmacogn Phytochem 9:408–410

Banakar SN, PrasannaKumar MK, Mahesh HB, Parivallal PB, Puneeth ME, Gautam C, Pramesh D, Shiva Kumara TN, Girish TR, Nori S, Narayan SS (2022) Red-seaweed biostimulants differentially alleviate the impact of fungicidal stress in rice (*Oryza sativa* L.). Sci Rep 12:5993

Banakar SN, Prasannakumar MK, Parivallal PB, Pramesh D, Mahesh HB, Sarangi AN, Puneeth ME, Patil SS (2023) Rice-*Magnaporthe* transcriptomics reveals host defense activation induced by red seaweed biostimulant in rice plants. Front Genet 14:1132561

Banu AT, Ramani PS, Murugan A (2020) Effect of seaweed coating on quality characteristics and shelf life of tomato (*Lycopersicon esculentum* Mill). Food Sci Hum Wellness 9:176–183

Begum M, Bordoloi BC, Singha DD, Ojha NJ (2018) Role of seaweed extract on growth, yield and quality of some agricultural crops: A review. Agric Rev 39:321–326

Beumer RR, Te Giffel MC, Cox LJ, Rombouts FM, Abee T (1994) Effect of exogenous proline, betaine, and carnitine on growth of *Listeria monocytogenes* in a minimal medium. Appl Environ Microbiol 60:1359–1363

Buschmann AH, Camus C, Infante J, Neori A, Israel Á, Hernández-González MC, Pereda SV, Gomez-Pinchetti JL, Golberg A, Tadmor-Shalev N, Critchley AT (2017) Seaweed production: overview of the global state of exploitation, farming and emerging research activity. Eur J Phycol 52:391–406

Carillo P, Ciarmiello LF, Woodrow P, Corrado G, Chiaiese P, Rouphael Y (2020) Enhancing sustainability by improving plant salt tolerance through macro-and micro-algal biostimulants. Biology (Basel) 9:253

Chaudhari N, Kothari D, Walia S, Ghosh A, Vaghela P, Kumar R (2023) Biostimulant enhances growth and corm production of saffron (*Crocus sativus* L.) in non-traditional areas of North western Himalayas. Front Plant Sci 14:1097682

Chauhan PS, Saxena A (2016) Bacterial carrageenases: an overview of production and biotechnological applications. 3 Biotech 6:146

da Costa MA, Alves HJ, Alab JC, Albrecht LP, Albrecht AJP, Marra BM (2017) *Kappaphycus alvarezii* extract used for the seed treatment of soybean culture. Afr J Agic Res 12:1054–1058

de Araújo Amatuzzi JC, do Nascimento Vieira L, Sant'Anna-Santos BF, Noseda MD, de Freitas Fraga HP (2020) Improved in vitro development of *Epidendrum secundum* (Orchidaceae) by using aqueous extract of the seaweed *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae). Acta Physiol Plant 42:1–9

de Castro TAVT, Tavares OCH, de Oliveira Torchia DF, da Silva HFO, de Moura OVT, Cantarino RE, de Abreu Lopes S, Viêgas CV, do Amaral Vendramini AL, Santos LA, Berbara RLL (2023) Organic fragments of k-carrageenan, lipids and peptides plus K-rich inorganic fraction in *Kappaphycus alvarezii* biomass are responsible for growth stimulus in rice plant when applied both foliar and root pathway. Algal Res 71:103040

Deb K, Singh S (2022) Effect of seaweed (*Kappaphycus alvarezii*) extract on rainfed aerobic rice (*Oryza sativa* L.). Environ Conserv J 23:260–266

Del Buono D (2020) Can biostimulants be used to mitigate the effect of anthropogenic climate change on agriculture? It is time to respond. Sci Total Environ 751:141763

Deolu-Ajayi AO, van der Meer IM, van der Werf A, Karlova R (2022) The power of seaweeds as plant biostimulants to boost crop production under abiotic stress. Plant Cell Environ 45:2537–2553

Devi NL, Mani S (2015) Effect of seaweed saps *Kappaphycus alvarezii* and *Gracilaria* on growth, yield and quality of rice. Indian J Sci Technol 8:1–6

Dilavarnaik S, Basavaraja PK, Yogendra ND, Ghosh A (2017) Influence of seaweed saps on germination, growth and yield of hybrid maize under Cauvery Command of Karnataka, India. Int J Curr Microbiol Appl Sci 6:1047–1056

Dutta SK, Layek J, Akoijam RS, Boopathi T, Saha S, Singh SB, Prakash N (2019) Seaweed extract as natural priming agent for augmenting seed quality traits and yield in *Capsicum frutescens* L. J Appl Phycol 31:3803–3813

Dwivedi SK, Ashok PK (2015) Impact of natural organic fertilizer (seaweed saps) on productivity, nutrient uptake and economics of greengram (*Phaseolus radiata* L.). Int J Environ Sci 7:461–466

Dutta SK, Layek J, Yadav A, Das SK, Rymbai H, Mandal S, Sahana N, Bhutia TL, Devi EL, Patel VB, Laha R (2023) Improvement of rooting and growth in kiwifruit (*Actinidia deliciosa*) cuttings with organic biostimulants. Heliyon 9:e17815

Dwivedi SK, Kumar A, Pal A, Sriwastava LK, Meshram M (2016) Effect of seaweed saps on growth, nutrient uptake and yield of potato (*Solanum tuberosum* L.). Appl Biol Res 18:1–7

Dwivedi SK, Meshram MR, Pal A, Pandey N, Ghosh A (2014) Impact of natural organic fertilizer (seaweed saps) on productivity and nutrient status of blackgram (*Phaseolus mungo* L.). Bioscan 9:1535–1539

El-Ashry AAEL, Gabr AMM, Arafa NM, El-Bahr MK (2019) Rutin accumulation in gardenia calli cultures as a response to phenyl alanine and salicylic acid. Bull Natl Res Cent 43:141

El Boukhari MEL, Barakate M, Bouhia Y, Lyamlouli K (2020) Trends in seaweed extract based biostimulants: Manufacturing process and beneficial effect on soil-plant systems. Plants 9:359

Eswaran K, Ghosh PK, Siddhanta AK, Patolia JS, Periyasamy C, Mehta AS, Mody KH, Ramavat BK, Prasad K, Rajyaguru MR, Reddy SKCR, Pandya JB, Tewari A (2005) Integrated method for production of carrageenan and liquid fertilizer from fresh seaweeds. USA Patent 2005/6893479.

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. FAO, Rome. 224 p

Garai S, Brahmachari K, Sarkar S, Kundu R, Pal M, Pramanick B (2019) Crop growth and productivity of rainy maize-garden pea copping sequence as influenced by *Kappaphycus* and *Gracilaria* saps at alluvial soil of West Bengal, India. Curr J Appl Sci Technol 36:1–11

Ghosh A, Vijayanand KG, Seth A (2015) Life cycle impact assessment of seaweed based biostimulant production from onshore cultivated *Kappaphycus alvarezii* (Doty) Doty ex Silva- Is it environmentally sustainable? Algal Res 12:513–521

Girish T, Vantharam V, Malhotra P, Bhose SP, Sekar N, Kuruvilla S, Girija L, Khandelwal S, Sanghe N, Kumar S, Nori SS (2020) Composition comprising sulphated galactose, and implementations thereof. PCT Patent Application 2019/050831

Hayashi L, Hurtado AQ, Msuya FE, Bleicher-Lhonneur G, Critchley AT (2010) A review of *Kappaphycus* farming: prospects and constraints. In: Israel A, Einav R, Seckbach J (eds) Seaweeds their role globally changing environment. Springer, Dordrecht, pp 255–283

Hayashi L, Reis RP (2012) Cultivation of the red algae *Kappaphycus alvarezii* in Brazil and its pharmacological potential. Rev Bras Farmacogn 22:748–752

Hoque MA, Banu MNA, Okuma E, Amako K, Nakamura Y, Shimoishi Y, Murata Y (2007) Exogenous proline and glycinebetaine increase NaCl-induced ascorbate–glutathione cycle enzyme activities, and proline improves salt tolerance more than glycinebetaine in tobacco Bright Yellow-2 suspension-cultured cells. J Plant Physiol 164:1457–1468

Hurtado AQ, Neish IC, Critchley AT (2019) Phyconomy: the extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming. Phycologia 58:472–483

Hurtado AQ, Neish IC, Majahar Ali MK, Norrie J, Pereira L, Michalak I, Shukla PS, Critchley AT (2021) Extracts of seaweeds used as biostimulants on land and sea crops—an efficacious, phyconomic, circular blue economy: with special reference to *Ascophyllum* (brown) and *Kappaphycus* (red) seaweeds. In: Gupta S, Van Staden J (eds) Biostimulants for crops from seed germination to plant development. Elsevier, London, pp. 263–288

Iswarya S, Latha KR, Srinivasan K (2019) Evaluation of seaweed extract on growth determinants, yield and biochemical parameters of greengram (*Vigna radiata*). J Pharmacogn Phytochem 8:1861–1864

Jadhao GR, Chaudhary DR, Khadse VA, Zodape ST (2015) Utilization of seaweeds in enhancing productivity and quality of black gram [*Vigna mungo* (L.) Hepper] for sustainable agriculture. Indian J Nat Prod Resour 6:16–22

Karthikeyan K, Shanmugam M (2017) The effect of potassium-rich biostimulant from seaweed *Kappaphycus alvarezii* on yield and quality of cane and cane juice of sugarcane var. Co 86032 under plantation and ratoon crops. J Appl Phycol 29:3245–3252

Karthikeyan K, Shanmugam M (2016a) Grain yield and functional properties of red gram applied with seaweed extract powder manufactured from *Kappaphycus alvarezii*. Intl J Recent Adv Multi Res 3:1353–1359

Karthikeyan K, Shanmugam M (2016b) Bio-stimulant of seaweed source as an organic alimentative to Bellary onion: Bulb yield and pyruvic acid levels. Am J Agric Res 1:1–9

Karthikeyan K, Shanmugam M (2015) Yield and oil content of peanut (var. TMV-7) and sunflower (var. Co-2) applied with biostimulant AQUASAP manufactured from seaweed. Afr J Agric Res 10:2537–2543

Karthikeyan K, Shanmugam M (2014) Enhanced yield and quality in some banana varieties applied with commercially manufactured biostimulant Aquasap from sea plant *Kappaphycus alvarezii*. J Agric Sci Technol B 4:621–631

Kaushal N, Gupta K, Bhandhari K, Kumar S, Thakur P, Nayyar H (2011) Proline induces heat tolerance in chickpea (*Cicer arietinum* L.) plants by protecting vital enzymes of carbon and antioxidative metabolism. Physiol Mol Biol Plants 17:203–213

Kavipriya R, Boominathan P (2018) Influence of biostimulants and plant growth regulators on physiological and biochemical traits in tomato (*Lycopersicon esculentum* Mill.). Madras Agric J 105:1–3

Khambhaty Y, Mody K, Gandhi MR, Thampy S, Maiti P, Brahmbhatt H, Eswaran K, Ghosh PK (2012) *Kappaphycus alvarezii* as a source of bioethanol. Bioresour Technol 103:180–185

Khan S, Yu H, Li Q, Gao Y, Sallam BN, Wang H, Liu P, Jiang W (2019) Exogenous application of amino acids improves the growth and yield of lettuce by enhancing photosynthetic assimilation and nutrient availability. Agronomy 9:266

Kim DR, Jeon CW, Cho G, Thomashow LS, Weller DM, Paik MJ, Lee YB, Kwak YS (2021) Glutamic acid reshapes the plant microbiota to protect plants against pathogens. Microbiome 9:244

Kumar KS, Ganesan K, Rao PVS (2015) Seasonal variation in nutritional composition of *Kappaphycus alvarezii* (Doty) Doty—an edible seaweed. J Food Sci Technol 52:2751–2760

Kumar R, Trivedi K, Anand KGV, Ghosh A (2020) Science behind biostimulant action of seaweed extract on growth and crop yield: insights into transcriptional changes in roots of maize treated with *Kappaphycus alvarezii* seaweed extract under soil moisture stressed conditions. J Appl Phycol 32:599–613

Kundu A, Mishra S, Kundu P, Jogawat A, Vadassery J (2022) *Piriformospora indica* recruits host-derived putrescine for growth promotion in plants. Plant Physiol 188:2289–2307

Layek J, Das A, Ghosh A, Marak MR, Krishnappa R, Ramkrushna GI, Panwar A, Devi S (2018) Valuation of sea weed saps on performance of tomato (*Lycopersicum esculentum*) under organic production system. Innov Farming 3:185–191

Layek J, Das A, Ghosh A, Sarkar D, Idapuganti RG, Boragohain J, Yadav GS, Lal R (2019) Foliar application of seaweed sap enhances growth, yield and quality of maize in eastern himalayas. Proc Natl Acad Sci India B 89:221–229

Layek J, Das A, Idapuganti RG, Sarkar D, Ghosh A, Zodape ST, Lal R, Yadav GS, Panwar AS, Ngachan S, Meena RS (2017) Seaweed extract as organic bio-stimulant improves productivity and quality of rice in eastern Himalayas. J Appl Phycol 30:547–558

Layek J, Das A, Ramkrushna GI, Trivedi K, Yesuraj D, Chandramohan M, Kubavat D, Agarwal PK, Ghosh A (2015) Seaweed sap: a sustainable way to improve productivity of maize in North-East India. Int J Environ Stud 72:305–315

Layek J, Dutta SK, Krishnappa R, Das A, Ghosh A, Mishra VK, Panwar AS, Hazarika S, Devi S, Kumar M, Buragohain J (2023) Productivity, quality and profitability enhancement of french bean, okra and tomato with seaweed extract application under North-Eastern Himalayan condition. Sci Hortic 309:111626

Lodhi KK, Choubey NK, Dwivedi SK, Pal A, Kanwar PC (2015) Impact of seaweed saps on growth, flowering behaviour and yield of soybean [*Glycine max* (L.) Merrill.]. Bioscan 10:479–483

Mahajan RV, Bhale VM, Deshmukh JP, Patil SP, Singrup PV (2017) Significance of marine algal sap as foliar nutrition on seed quality and nutrient uptake of blackgram [*Vigna mungo*]. Int J Pure Appl Biosci 5:1042–1047

Mantri VA, Ashok KS, Musamil TM, Gobalakrishnan M, Saminathan KR, Behera DP, Veeragurunathan V, Eswaran K, Thiruppathi S, Pothal JK, Ghosh PK (2017a) Tube-net farming and device for efficient tissue segregation for industrially important agarophyte *Gracilaria edulis* (Rhodophyta). Aquac Eng 77:132–135

Mantri VA, Eswaran K, Shanmugam M, Ganesan M, Veeragurunathan V, Thiruppathi S, Reddy CRK, Seth A (2017b) An appraisal on commercial farming of *Kappaphycus alvarezii* in India: success in diversification of livelihood and prospects. J Appl Phycol 29:335–357

Mantri VA, Ghosh A, Eswaran K, Ganesan M (2022) Notes on recommendations for enabling policy interventions in the seaweed cultivation and processing domain in india. Sustainability 14:10416

Meinita MDN, Kang J-Y, Jeong G-T, Koo HM, Park SM, Hong Y-K (2012) Bioethanol production from the acid hydrolysate of the carrageenophyte *Kappaphycus alvarezii* (cottonii). J Appl Phycol 24:857–862

Mohammadipour N, Souri MK (2019) Effects of different levels of glycine in the nutrient solution on the growth, nutrient composition, and antioxidant activity of coriander (*Coriandrum sativum* L.). Acta Agrobot 72:1759

Mondal D, Ghosh A, Prasad K, Singh S, Bhatt N, Zodape ST, Chaudhary JP, Chaudhari J, Chatterjee PB, Seth A, Ghosh PK (2015) Elimination of gibberellin from *Kappaphycus alvarezii* seaweed sap foliar spray enhances corn stover production without compromising the grain yield advantage. Plant Growth Regul 75:657–666

Mondal D, Sharma M, Maiti P, Prasad K, Meena R, Siddhanta AK, Bhatt P, Ijardar S, Mohandas VP, Ghosh A, Eswaran K, Shah BG, Ghosh PK (2013) Fuel intermediates, agricultural nutrients and pure water from *Kappaphycus alvarezii* seaweed. RSC Adv 3:17989–17997

Nasibi F, Kalantari KM, Zanganeh R, Mohammadinejad G, Oloumi H (2016) Seed priming with cysteine modulates the growth and metabolic activity of wheat plants under salinity and osmotic stresses at early stages of growth. Indian J Plant Physiol 21:279–286

Nori SS, Kumar S, Khandelwal S, Suryanarayan S (2019) Biostimulant formulation for improving plant growth and uses thereof. USA Patent 2019/10358391

Nouwen N, Gargani D, Giraud E (2019) The modification of the flavonoid naringenin by *Bradyrhizobium* sp. Strain ORS285 changes the nod genes inducer function to a growth stimulator. Mol Plant-Microbe Interact 32:1517–1525

Pal A, Dwivedi SK, Kanwar PC (2015a) Effect of seaweed saps on increase yield, nutrient uptake and soil nutrient balance sheet of rice (*Oryza sativa* L.). The Ecoscan 9:531–535

Pal A, Dwivedi SK, Maurya PK, Kanwar P (2015b) Effect of seaweed saps on growth, yield, nutrient uptake and economic improvement of maize (sweet corn). J Appl Nat Sci 7:970–975

Panichikkal J, Edayileveetil Krishnankutty R (2020) Rhizobacterial biofilm and plant growth promoting trait enhancement by organic acids and sugars. Biofouling 36:990–999

Patel K, Agarwal P, Agarwal PK (2018) *Kappaphycus alvarezii* sap mitigates abiotic-induced stress in *Triticum durum* by modulating metabolic coordination and improves growth and yield. J Appl Phycol 30:2659–2673

Paulert R, Stadnik MJ (2019) Macroalgae polysaccharides in plant defense responses. In: Pereira L, Bahcevandziev K, Joshi NH (eds) Seaweeds as plant fertilizer, agricultural biostimulants and animal fodder. CRC Press, Boca Raton, pp 23–45

Pedley KF, Martin GB (2004) Identification of MAPKs and their possible MAPK kinase activators involved in the pto-mediated defense response of tomato. J Biol Chem 279:49229–49235

Piotrowska-Niczyporuk A, Bajguz A, Kotowska U, Bralska M, Talarek-Karwel M (2018) Growth, metabolite profile, oxidative status, and phytohormone levels in the green alga *Acutodesmus obliquus* exposed to exogenous auxins and cytokinins. J Plant Growth Regul 37:1159–1174

Posmyk MM, Janas KM (2007) Effects of seed hydropriming in presence of exogenous proline on chilling injury limitation in *Vigna radiata* L. seedlings. Acta Physiol Plant 29:509–517

Pongtongkam P, Peyachoknagul S, Sripichit P, Thongpan A, Klakhaeng K, Ketsagul S, Lertsirirungson K (2004) Effects of L-lysine on callus formation, plant regeneration and flowering of Thai rice cv KDML 105. Agric Nat Res 38:190–195

Prajapati A, Patel CK, Singh N, Jain SK, Chongtham SK, Maheshwari MN, Patel CR, Patel RN (2016) Evaluation of seaweed extract on growth and yield of potato. Environ Ecol 34:605–608

Pramanick B, Brahmachari K, Ghosh A (2013) Effect of seaweed saps on growth and yield improvement of green gram. Afr J Agric Res 8:1180–1186

Pramanick B, Brahmachari K, Ghosh A, Zodape ST (2016) Effect of seaweed saps derived from two marine algae *Kappaphycus* and *Gracilaria* on growth and yield improvement of blackgram. Indian J Geo-Mar Sci 45:789–794

Pramanick B, Brahmachari K, Ghosh A, Zodape ST (2014a) Effect of seaweed saps on growth and yield improvement of transplanted rice in old alluvial soil of West Bengal. Bangladesh J Bot 43:53–58

Pramanick B, Brahmachari K, Ghosh A, Zodape ST (2014b) Foliar nutrient management through *Kappaphycus* and *Gracilaria* saps in rice-potato-green gram crop sequence. J Sci Ind Res (India) 73:613–617

Pramanick B, Brahmachari K, Ghosh D, Bera PS (2018) Influence of foliar application seaweed (*Kappaphycus* and *Gracilaria*) saps in rice (*Oryza sativa*)-potato (*Solanum tuberosum*)-blackgram (*Vigna mungo*) sequence. Indian J Agron 63:8–13

Pramanick B, Brahmachari K, Kar S, Mahapatra BS (2020) Can foliar application of seaweed sap improve the quality of rice grown under rice–potato–greengram crop sequence with better efficiency of the system? J Appl Phycol 32:3377–3386

Pramanick B, Brahmachari K, Mahapatra BS, Ghosh A, Ghosh D, Kar S (2017) Growth, yield and quality improvement of potato tubers through the application of seaweed sap derived from the marine alga *Kappaphycus alvarezii*. J Appl Phycol 29:3253–3260

Prithiviraj B, Perry LG, Badri DV, Vivanco JM (2007) Chemical facilitation and induced pathogen resistance mediated by a root-secreted phytotoxin. New Phytol 173:852–860

Raj Y, Ali N, Pati AM, Kumar R (2022) Cleaner production technologies for the amelioration of soil health, biomass and secondary metabolites in *Ocimum basilicum* L. under Indian Western Himalaya. Front Plant Sci 13:976295

Rathore SS, Chaudhary DR, Boricha GN, Ghosh A, Bhatt BP, Zodape ST, Patolia JS (2009) Effect of seaweed extract on the growth, yield and nutrient uptake of soybean (*Glycine max*) under rainfed conditions. S Afr J Bot 75:351–355

Raverkar KP, Pareek N, Chandra R, Chauhan S, Zodape ST, Ghosh A (2016) Impact of foliar application of seaweed saps on yield, nodulation and nutritional quality in green gram (*Vigna radiata* L). Legume Res 39:315–318

Reddy CRK, Kumar GRK, Siddhanta AK, Tewari A, Eswaran K (2003) In vitro somatic embryogenesis and regeneration of somatic embryos from pigmented callus of *Kappaphycus alvarezii* (Doty) Doty (Rhodophyta, Gigartinales). J Phycol 39:610–616

Ricci M, Tilbury L, Daridon B, Sukalac K (2019) General principles to justify plant biostimulant claims. Front Plant Sci 10:494

Rivero RM, Shulaev V, Blumwald E (2009) Cytokinin-dependent photorespiration and the protection of photosynthesis during water deficit. Plant Physiol 150:1530–1540

Rover S, de Freitas MB, Barcelos-Oliveira JL, Stadnik MJ (2022) An algal extract enriched with amino acids increases the content of leaf pigments but also the susceptibility to the powdery mildew of lettuce. Phytoparasitica. https://doi.org/10.1007/s12600-022-01000-7

Roy A, Ghosh D, Kasera M, Nori S, Vemanna RS, Mohapatra S, Narayan SS, Bhattacharjee S (2022) *Kappaphycus alvarezii*-derived formulations enhance salicylic acid-mediated anti-bacterial defenses in *Arabidopsis thaliana* and rice. J Appl Phycol 34:679–695

Sahana BN, PrasannaKumar MK, Mahesh HB, Buela Parivallal P, Puneeth ME, Gautam C, Girish TR, Nori S, Suryanarayan S (2022) Biostimulants derived from red seaweed stimulate the plant defence mechanism in rice against *Magnaporthe oryzae*. J Appl Phycol 34:659–665

San PT, Khanh CM, Khanh HHN, Khoa TA, Hoang N, Nhung LT, Trinh NTK, Nguyen TD (2020) k-Oligocarrageenan promoting growth of hybrid maize: influence of molecular weight. Molecules 25:3825

Shah MT, Zodape ST, Chaudhary DR, Eswaran K, Chikara J (2013) Seaweed sap as an alternative liquid fertilizer for yield and quality improvement of wheat. J Plant Nutr 36:192–200

Shanmugam M, Seth A (2018) Recovery ratio and quality of an agricultural bio-stimulant and semi-refined carrageenan co-produced from the fresh biomass of *Kappaphycus alvarezii* with respect to seasonality. Algal Res 32:362–371

Shankar T, Malik GC, Banerjee M, Ghosh A (2020) Influence of sea weeds extracts on the growth, quality and productivity of sesame (*Sesamum indicum*) in the red and lateritic belt of West Bengal. Int J Bioresour Sci 7:5–9

Sharma A, Datt C (2020) Effect of red seaweed *Kappaphycus alvarezii* based feed additive on feed intake, nutrient utilization and nitrogen balance in lactating crossbred cows. J Entomol Zool Stud 8:487–490

Sharma M, Mondal D, Das AK, Prasad K (2014) Production of partially reduced graphene oxide nanosheets using a seaweed sap. RSC Adv 4:64583–64588

Sharma A, Datt C, Gupta R, Kumar JS, Tyagi A, Mani V (2019) Effect of supplementation of *Kappaphycus alvarezii* based seaweed product on rumen fermentation parameters under in vitro conditions. Indian J Dairy Sci 72:514–517

Sharma Loknath, Banerjee Mahua, Malik GC, gopalakrishnan vijay anand, Zodape SK, Ghosh Arup (2017) Sustainable agro-technology for enhancement of rice production in the red and lateritic soils using seaweed based biostimulants. J Cleaner Product 149:968–975.

Singh S, Singh MK, Singh AK, Singh CS (2015a) Application of seaweed sap (*Kappaphycus alvarezii* and *Gracilaria edulis*) for higher productivity of maize (*Zea mays* L.). Res J Agric Sci 6:232–234

Singh S, Singh MK, Pal SK, Thakur R, Zodape ST, Ghosh A (2015b) Use of seaweed sap for sustainable productivity of maize. Bioscan 10:1349–1355

Shinde S, Madathil MM (2018) *Kappaphycus* active ingredient compositions for modulating plant characteristics. USA patent 2018/075948

Shukla PS, Borza T, Critchley AT, Prithiviraj B (2016) Carrageenans from red seaweeds as promoters of growth and elicitors of defense response in plants. Front Mar Sci 3:81

Shukla PS, Gupta K, Agarwal P, Jha B, Agarwal PK (2015) Overexpression of a novel SbMYB15 from *Salicornia brachiata* confers salinity and dehydration tolerance by reduced oxidative damage and improved photosynthesis in transgenic tobacco. Planta 242:1291–1308

Shukla PS, Mantin EG, Adil M, Bajpai S, Critchley AT, Prithiviraj B (2019) *Ascophyllum nodosum*-based biostimulants: Sustainable applications in agriculture for the stimulation of plant growth, stress tolerance, and disease management. Front Plant Sci 10:655

Shukla PS, Yadav NS, Critchley AT, Prithiviraj B (2022) Editorial: Biostimulants as an avenue of abiotic stress tolerance improvement in crops. Front Sustain Food Syst 6:908555

Shukla PS, Nivetha N, Nori SS, Bose D, Kumar S, Khandelwal S, Critchley A, Suryanarayan S (2023) Understanding the mode of action of AgroGain®, a biostimulant derived from the red seaweed *Kappaphycus alvarezii* in the stimulation of cotyledon expansion and growth of *Cucumis sativa* (cucumber). Front Plant Sci 14:1136563

Sible CN, Seebauer JR, Below FE (2021) Plant Biostimulants: A categorical review, their implications for row crop production, and relation to soil health indicators. Agronomy 11:1297

Simatupang NF, Pong-Masak PR, Ratnawati P, Agusman Paul NA, Rimmer MA (2021) Growth and product quality of the seaweed *Kappaphycus alvarezii* from different farming locations in Indonesia. Aquac Rep 20:100685

Singh I, Anand KGV, Solomon S, Shukla SK, Rai R, Zodape ST, Ghosh A (2018) Can we not mitigate climate change using seaweed based biostimulant: A case study with sugarcane cultivation in India. J Clean Prod 204:992–1003

Singh S, Singh MK, Pal SK, Trivedi K, Yesuraj D, Singh CS, Anand KGV, Chandramohan M, Patidar R, Kubavat D, Zodape ST, Ghosh A (2015c) Sustainable enhancement in yield and quality of rain-fed maize through *Gracilaria edulis* and *Kappaphycus alvarezii* seaweed sap. J Appl Phycol 28:2099–2112

Sivanandhan G, Mariashibu TS, Arun M, Rajesh M, Kasthurirengan S, Selvaraj N, Ganapathi A (2011) The effect of polyamines on the efficiency of multiplication and rooting of *Withania somnifera* (L.) Dunal and content of some withanolides in obtained plants. Acta Physiol Plant 33:2279–2288

Steenackers W, El Houari I, Baekelandt A, Witvrouw K, Dhondt S, Leroux O, Gonzalez N, Corneillie S, Cesarino I, Inzé D, Boerjan W, Vanholme B (2019) *cis*-Cinnamic acid is a natural plant growth-promoting compound. J Exp Bot 70:6293–6304

Trivedi K, Anand KGV, Kubavat D, Ghosh A (2022a) Role of *Kappaphycus alvarezii* seaweed extract and its active constituents, glycine betaine, choline chloride, and zeatin in the alleviation of drought stress at critical growth stages of maize crop. J Appl Phycol 34:1791–1804

Trivedi K, Gopalakrishnan VAK, Kumar R, Ghosh A (2021) Transcriptional analysis of maize leaf tissue treated with seaweed extract under drought stress. Front Sustain Food Syst 5:774978

Trivedi K, Kumar R, Vijay Anand KG, Bhojani G, Kubavat D, Ghosh A (2022b) Structural and functional changes in soil bacterial communities by drifting spray application of a commercial red seaweed extract as revealed by metagenomics. Arch Microbiol 204:72

Trivedi K, Vijay Anand KG, Kubavat D, Kumar R, Vaghela P, Ghosh A (2017) Crop stage selection is vital to elicit optimal response of maize to seaweed bio-stimulant application. J Appl Phycol 29:2135–2144

Trivedi K, Vijay Anand KG, Kubavat D, Patidar R, Ghosh A (2018a) Drought alleviatory potential of *Kappaphycus* seaweed extract and the role of the quaternary ammonium compounds as its constituents towards imparting drought tolerance in *Zea mays* L. J Appl Phycol 30:2001–2015

Trivedi K, Vijay Anand KG, Vaghela P, Ghosh A (2018b) Differential growth, yield and biochemical responses of maize to the exogenous application of *Kappaphycus alvarezii* seaweed extract, at grain-filling stage under normal and drought conditions. Algal Res 35:236–244

Vaghela P, Das AK, Trivedi K, Anand KGV, Shinde P, Ghosh A (2022) Characterization and metabolomics profiling of *Kappaphycus alvarezii* seaweed extract. Algal Res 66:102774

Vaghela P, Trivedi K, Anand KGV, Brahmbhatt H, Nayak J, Khandhediya K, Prasad K, Moradiya K, Kubavat D, Konwar LJ, Veeragurunathan V, Grace PG, Ghosh A (2023) Scientific basis for the use of minimally processed homogenates of *Kappaphycus alvarezii* (red) and *Sargassum wightii* (brown) seaweeds as crop biostimulants. Algal Res 70:102969

Vera J, Castro J, Contreras RA, González A, Moenne A (2012) Oligo-carrageenans induce a long-term and broad-range protection against pathogens in tobacco plants (var. Xanthi). Physiol Mol Plant Pathol 79:31–39

Vera J, Castro J, Gonzalez A, Moenne A (2011) Seaweed polysaccharides and derived oligosaccharides stimulate defense responses and protection against pathogens in plants. Mar Drugs 9:2514–2525

Vinod S, Natarajan K, Santhanu K, Selvakumar D, Natesan S, Senthil K (2022) Effect of seaweed elicitation and culture conditions on biomass and metabolite production in in vitro shoots of *Withania somnifera*. S Afr J Bot 151:781–790

Wanyonyi S, Du Preez R, Brown L, Paul NA, Panchal SK (2017) *Kappaphycus alvarezii* as a food supplement prevents diet-induced metabolic syndrome in rats. Nutrients 9:1261

Windisch S, Walter A, Moradtalab N, Walker F, Höglinger B, El-Hasan A, Ludewig U, Neumann G, Grosch R (2021) Role of Benzoic acid and lettucenin a in the defense response of lettuce against soil-borne pathogens. Plants 10:2336

Wozniak E, Blaszczak A, Wiatrak P, Canady M (2020) Biostimulant mode of action: impact of biostimulant on whole-plant level. In: Geelen D, Xu L (eds) The chemical biology of plant biostimulants. John Wiley & Sons, pp 205–227.

Basavaraja PK, Yogendra ND, Zodape ST, Prakash R, Ghosh A (2018) Effect of seaweed sap as foliar spray on growth and yield of hybrid maize. J Plant Nutr 41:1851–1861

Yong YS, Yong WTL, Ng SE, Anton A, Yassir S (2015) Chemical composition of farmed and micropropagated *Kappaphycus alvarezii* (Rhodophyta, Gigartinales), a commercially important seaweed in Malaysia. J Appl Phycol 27:1271–1275

Zhao C, Zayed O, Yu Z, Jiang W, Zhu P, Hsu CC, Zhang L, Tao WA, Lozano-Durán R, Zhu JK (2018) Leucine-rich repeat extensin proteins regulate plant salt tolerance in *Arabidopsis*. Proc Natl Acad Sci 115:13123–13128

Zhu C, Chen Z (2005) Role of polyamines in adventitious shoot morphogenesis from cotyledons of cucumber in vitro. Plant Cell Tissue Organ Cult 81:45–53

Zodape ST, Gupta A, Bhandari SC, Rawat US, Chaudhary DR, Eswaran K, Chikara J (2011) Foliar application of seaweed sap as biostimulant for enhancement of yield and quality of tomato (*Lycopersicon esculentum* Mill.). J Sci Indust Res 70:215–219

Zodape ST, Kawarkhe VJ, Patolia JS, Warade AD (2008) Effect of liquid seaweed fertilizer on yield and quality of okra (*Abelmoschus esculentus* L.). J Sci Indust Res 67:1115–1117

Zodape ST, Mukherjee S, Reddy MP, Chaudhary DR (2012) Effect of *Kappaphycus alvarezii* (Doty) Doty ex Silva. extract on grain quality, yield and some yield components of wheat (*Triticum aestivum* L.). Int J Plant Prod 3:97–101

Zodape ST, Mukhopadhyay S, Eswaran K, Reddy MP, Chikara J (2010) Enhanced yield and nutritional quality in green gram (*Phaseolus radiata* L) treated with seaweed (*Kappaphycus alvarezii*) extract. J Sci Indust Res 69:468–471

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